

# Measurements and analysis of helium-like triplet ratios in the X-ray spectra of O-type stars

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## ABSTRACT

We discuss new methods of measuring and interpreting the forbidden-to-intercombination line ratios of helium-like triplets in the X-ray spectra of O-type stars, including accounting for the spatial distribution of the X-ray emitting plasma and using the detailed photospheric UV spectrum. Measurements are made for four O stars using archival *Chandra* HETGS data. We assume an X-ray emitting plasma spatially distributed in the wind above some minimum radius  $R_0$ . We find minimum radii of formation typically in the range of  $1.25 < R_0/R_* < 1.67$ , which is consistent with results obtained independently from line profile fits. We find no evidence for anomalously low  $f/i$  ratios and we do not require the existence of X-ray emitting plasmas at radii that are too small to generate sufficiently strong shocks.

*Subject headings:* stars: early type — star: winds, outflows — techniques: spectroscopic — stars: individual ( $\zeta$  Pup,  $\zeta$  Ori,  $\iota$  Ori,  $\delta$  Ori)

## 1. Introduction

Since the discovery of X-ray emission from OB stars by *Einstein* (Harnden et al. 1979; Seward et al. 1979), the exact mechanism for X-ray production has been something of a mystery. X-ray emission from OB stars had been predicted by Cassinelli & Olson (1979), who proposed that an X-ray emitting corona could explain the observation of superionized O VI through Auger ionization of O IV. However, subsequent observations showing less attenuation of soft X-rays than would be expected from a corona lying below a dense stellar wind made a purely coronal origin seem unlikely (Cassinelli & Swank 1983). Macfarlane et al. (1993) also found that a distributed X-ray source was necessary to explain the observed O VI UV P Cygni profile in  $\zeta$  Pup. Furthermore, with no expectation of a solar-type  $\alpha - \Omega$  dynamo in OB stars with radiative envelopes, the coronal model fell out of favor. Subsequently, several scenarios in which magnetic field generation and dynamos could exist in OB stars have been proposed (Charbonneau & MacGregor 2001; MacGregor & Cassinelli 2003; Mullan & MacDonald 2005). Since these models have been proposed, the primary observational evidence invoked by their proponents is anomalously low  $f/i$  ratios in the X-ray emission of a few He-like ions in several stars. Re-examining these line ratios and determining whether they require a coronal model to explain them is one of the main goals of this paper.

Shocks arising from instabilities in the star's radiatively driven wind have been considered to provide a more likely origin for the observed X-ray emission, as they are expected to be present, given the line-driven nature of these winds (Lucy & White 1980; Lucy 1982; Krolik & Raymond 1985; Owocki, Castor, & Rybicki 1988; Feldmeier 1995). However, there have been difficulties in reproducing the observed X-ray properties of O stars, such as the overall X-ray luminosity and the spectral energy distribution, from stellar wind instability models (Hillier et al. 1993; Feldmeier 1995; Feldmeier et al. 1997a,b). Until recently, the quality of the available spectral data provided little insight into these problems, since the CCD and proportional counter spectra could not resolve individual spectral lines.

Recent high resolution X-ray spectroscopy of OB stars by the XMM-*Newton* Reflection Grating Spectrometer (RGS) (Kahn et al. 2001; Mewe et al. 2003; Raassen et al. 2005) and the *Chandra* High Energy Transmission Grating Spectrometer (HETGS) (Schulz et al. 2000; Waldron & Cassinelli 2001; Cassinelli et al. 2001; Miller et al. 2002; Cohen et al. 2003; Kramer et al. 2003; Gagné et al. 2005; Cohen et al. 2006) have answered some questions while raising new ones. Some stars have X-ray spectra that appear consistent with emission from shocks in the wind, but the detailed comparisons to predicted spectral models are still problematic. Both Waldron & Cassinelli (2001) and Cassinelli et al. (2001) have found low forbidden-to-intercombination line ratios in one set of helium-like triplets each in the X-ray spectra of  $\zeta$  Ori and  $\zeta$  Pup. They infer from this that some of the X-ray emitting plasma is

too close to the star to allow shocks of sufficient velocity to develop.

Other stars ( $\theta^1$  Ori C and  $\tau$  Sco) have X-ray spectra that are unusually hard and have relatively small line widths. While these stars might be considered prime candidates for a coronal model of X-ray emission - especially after having magnetic fields detected via Zeeman splitting (Donati et al. 2002, 2006) - their behavior is better understood in terms of the magnetically channeled wind shock model, rather than a model of magnetic heating (Schulz et al. 2000; Cohen et al. 2003; Schulz et al. 2003; Gagné et al. 2005; Donati et al. 2006).

Finally, we note that for all of the O giants and supergiants observed, the line profiles are less asymmetric than predicted, given the high mass-loss rates measured for these stars using radio free-free emission, H  $\alpha$  emission, and UV absorption lines (Waldron & Cassinelli 2001; Kahn et al. 2001; Cassinelli et al. 2001; Miller et al. 2002; Kramer et al. 2003; Cohen et al. 2006). This implies either a lower effective opacity to X-rays in their winds (e.g. due to clumping or porosity effects (Feldmeier et al. 2003; Oskinova et al. 2004, 2006; Owocki & Cohen 2006)), or lower mass-loss rates (Crowther et al. 2002; Massa et al. 2003; Hillier et al. 2003; Bouret et al. 2005; Fullerton et al. 2006).

One of the key diagnostic measurements available to us in understanding the nature of X-ray emission in OB stars is the forbidden-to-intercombination line ratio in the emission from ions that are isoelectronic with helium. This ratio is sensitive to the UV flux, and thus to the proximity to the stellar surface. This allows us to constrain the location of the X-ray emitting plasma independently of other spectral data, such as emission line profile shapes.

In this paper we discuss methods for using the  $f/i$  ratio to constrain the location of X-ray emitting plasma in O star winds. In particular, we explore the effects of a spatially distributed source motivated by the broad line profiles. We discuss the effects of photospheric absorption lines, as well as the  $f/i$  ratio expected for a plasma emitted over a range of radii, taking account of detailed line shapes when signal-to-noise allows. We find that accounting in detail for photospheric absorption lines is not important, as long as the X-ray emission originates over a range of radii.

These methods are then applied to He-like triplet emission in a set of archival *Chandra* observations of O stars. Our primary result is that good fits can be achieved for most lines with models having emission distributed over the wind, with minimum radii of about 1.5 stellar radii. We find that none of the data require the X-ray emitting plasma to be formed very close to the photosphere.

This paper is organized as follows: In § 2 we review the physics of line formation in He-like species (§ 2.1), explore the effects of spectral structure in the photoexciting UV field

(§ 2.2), and of spatial distribution of the X-ray emitting plasma (§ 2.3), while incorporating the line-ratio modeling into a self-consistent line-profile model (§ 2.4). In § 3 we discuss the reduction and analysis of archival O star X-ray spectra. In § 4 we give the results of this analysis, fitting high signal-to-noise complexes with the self-consistent line-profile model described in § 2.4 and fitting the lower signal-to-noise complexes with multiple Gaussians and interpreting these results according to the spatially distributed picture described in § 2.3. In § 5 we discuss the implications of these results, and in § 6 we give our conclusions.

## 2. Model

### 2.1. Radial dependence of the $f/i$ ratio

The physics of helium-like ions in coronal plasmas has been investigated in numerous papers (Gabriel & Jordan 1969; Blumenthal et al. 1972; Gabriel & Jordan 1973; Mewe & Schrijver 1975, 1978a,b,c; Pradhan & Shull 1981; Pradhan 1982; Porquet et al. 2001). The principal diagnostic is the ratio of the strengths of the forbidden to intercombination lines,  $\mathcal{R} \equiv f/i$ . We will use the calligraphic  $\mathcal{R}$  to refer to this ratio, and the italic  $R$  to refer to distances comparable to the stellar radius.

The upper level of the forbidden line ( $2^3S_1$ ) is metastable and relatively long-lived. When the excitation rate from  $2^3S_1$  to the upper levels of the intercombination line ( $2^3P_{1,2}$ ) becomes comparable to the decay rate of the forbidden transition, the line ratio is altered.<sup>1</sup> The excitations may be due to electron impacts in a high density plasma, or due to an external UV radiation source.

Gabriel & Jordan (1969) (hereafter GJ) and Blumenthal, Drake, & Tucker (1972) (hereafter BDT) derive the expression

$$\mathcal{R} = \mathcal{R}_0 \frac{1}{1 + \phi/\phi_c + n_e/n_c} \quad (1)$$

where  $\phi$  is the photoexcitation rate from  $2^3S$  to  $2^3P$ , and  $\phi_c$  is the critical rate at which  $\mathcal{R}$  is reduced to  $\mathcal{R}_0/2$ . Similarly,  $n_e$  is the electron density, and  $n_c$  is the critical density.

In Table 1 we give our adopted values for the atomic parameters necessary for calculation of He-like triplet ratios. We adopt the BDT values for  $\phi_c$  because they have calculated it for

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<sup>1</sup>The  $2^3S_1$  state may also be excited to the  $2^3P_0$  state, but this state does not decay to ground, so we omit it from our discussion. However, in Gabriel & Jordan (1969) and Blumenthal, Drake, & Tucker (1972), the formal treatment involves all states.

all the ions we are interested in, and because more recent calculations are not substantially different. However, we use the more recent values for  $\mathcal{R}_0$  from Porquet et al. (2001); their calculations of  $\mathcal{R}_0$  are slightly lower than those of BDT. Porquet et al. (2001) also give values for  $G \equiv (f + i)/r$ , evaluated at  $T_{max}$ , the temperature at which emission from that He-like ion is the strongest. We cite  $G(T_{max})$  for comparison with our measurements.

Because densities high enough to cause a change in the line ratios exist only very close to the star, we consider only the photoexcitation term. If there are O stars with  $f/i$  ratios that are measured to be too low to be explained by photoexcitation, it is appropriate to consider the effects of high density; this is not the case for any of our measurements.

The expression for  $\phi$  may be evaluated as follows, given a model stellar atmosphere Eddington flux  $H_\nu$ :

$$\phi = \frac{16\pi^2 e^2}{m_e c} f \frac{H_\nu}{h\nu} W(r) \quad (2)$$

where  $W(r) = \frac{1}{2}(1 - \sqrt{1 - (R_*/r)^2})$  is the geometrical dilution.

The expression for the  $\mathcal{R}$  ratio derived by GJ is written such that  $f$  is the sum of the oscillator strengths for  $2^3S_1$  to all three of  $2^3P_J$ , despite the fact that  $2^3P_0$  does not decay to ground, and  $2^3P_2$  only contributes for high  $Z$ . For low  $Z$  (Ne IX and lower)  $H_\nu$  should be evaluated for  $2^3S_1 \rightarrow 2^3P_1$ . For Mg XI and higher  $Z$  ions it is more accurate to evaluate  $H_\nu$  for both  $2^3S_1 \rightarrow 2^3P_1$  and  $2^3P_2$  and weight the average by the relative contributions to the effective branching ratio. Of course, this is only necessary if  $H_\nu$  is substantially different for the two transitions.

Since the flux of UV radiation seen by ions in a stellar wind decreases in proportion to the geometrical dilution factor  $W(r)$ , the  $\mathcal{R}$  ratio is also a function of radius. It is helpful to express it in this form:

$$\mathcal{R}(r) = \mathcal{R}_0 \frac{1}{1 + 2P W(r)} \quad (3)$$

with  $P = \phi_*/\phi_c$  and

$$\phi_* = 8\pi \frac{\pi e^2}{m_e c} f \frac{H_\nu}{h\nu}. \quad (4)$$

The value of the  $\mathcal{R}$  ratio near the photosphere is then  $\mathcal{R}_{ph} = \mathcal{R}_0/(1 + P)$ .

In this paper we perform calculations and make measurements for a sample of four O stars observed by *Chandra*:  $\zeta$  Pup,  $\zeta$  Ori,  $\iota$  Ori, and  $\delta$  Ori. The relevant properties of these stars are given in Table 2. The effective temperatures and gravities of the stars are taken

from Lamers & Leitherer (1993) and then rounded off to the closest values calculated on the TLUSTY O star grid (Lanz & Hubeny 2003).

## 2.2. The effect of photospheric absorption lines

The expression for  $\mathcal{R}(r)$  written in the last paragraph involves an approximation that must be explored further. We assumed a photospheric UV flux that would be diluted by geometry, but we neglected the Doppler shift of the absorbing ions. Over the range of Doppler shifts seen in a stellar wind, there can be many photospheric absorption lines. This introduces an additional radial dependence to the photoexcitation rate, and thus the  $\mathcal{R}$  ratio:

$$\phi(r) \propto H_{\nu(r)} W(r) \quad (5)$$

with the Doppler shifted frequency as seen by an ion at radius  $r$ :

$$\nu(r) = \nu_0 \left( 1 + \frac{v(r)}{c} \right) \quad (6)$$

In this expression a positive velocity represents a blue shift.

In Figure 1 we show a plot of the photospheric UV flux for a model representing  $\zeta$  Ori near the  $2^3S_1 \rightarrow 2^3P_{1,2}$  transitions of Mg XI. The model is taken from the TLUSTY O star model grid (Lanz & Hubeny 2003). Note that for Mg XI, most of the intercombination line strength still arises from the  $2^3P_1$  to ground transition.

We also compute the  $\mathcal{R}$  ratio using an averaged value of  $H_\nu$ , which we compare to the  $\mathcal{R}$  ratio calculated using the non-averaged (radially dependent)  $H_\nu$ . We do this to understand whether it is important to explicitly account for photospheric absorption lines, or whether it is sufficient to calculate  $\mathcal{R}$  using an averaged value of the photospheric UV flux. We use the average value of  $H_\nu$  over the range where  $0.1 < \mathcal{R}/\mathcal{R}_0 < 0.9$ , or  $9 > 2P W(r) > 0.111$ . There are two reasons for this: when the photoexcitation rate is much less than the critical rate, the effect of photospheric lines on  $\mathcal{R}$  is small; and when the photoexcitation rate is so high that the forbidden line is very weak, we can't measure variations in the forbidden line strength. We estimate this range using the continuum UV flux. In cases where  $\mathcal{R}$  does not ever get reduced to  $0.1\mathcal{R}_0$  (even at the photosphere) because the UV flux is not strong enough, we average from the rest frequency to the frequency at which  $\mathcal{R} = 0.9\mathcal{R}_0$ .

In Figure 2 the dashed lines show  $\mathcal{R}(r)$  for averaged and non-averaged  $H_\nu$  for Mg XI for the star  $\zeta$  Ori. There are substantial fluctuations in  $\mathcal{R}(r)$  for the non-averaged case. The solid lines in the figure are discussed in the following section; they represent the effects of averaging the emission over a range of radii, as opposed to simply over a range of frequencies.

In making this figure we have ignored all additional Doppler shifts, as the purpose of the plot is mainly to illustrate qualitatively the effect of photospheric absorption lines on the  $\mathcal{R}$  ratio. Examples of potentially relevant Doppler shifts are the thermal velocities of the ions (of order  $100 \text{ km s}^{-1}$  for neon at 0.4 keV), stellar rotation (typically  $100 - 200 \text{ km s}^{-1}$  for O-type stars, although the wind also rotates), and the non-monotonicity of the stellar wind due to shocks (e.g. Feldmeier 1995, of order a few  $100 \text{ km s}^{-1}$ ). We have also treated the star as a point source rather than a finite disk, which would change the projected velocity as a function of position on the stellar disk. All of these effects are small compared to the wind terminal velocity, but they could diminish the impact of photospheric lines on the  $f/i$  ratio by smearing out the photospheric spectrum.

One possibly important effect we neglect is scattering by resonance lines of ions in the wind. This is probably relevant only for Mg XI. In this case the O VI line at  $1031.91 \text{ \AA}$  is on the blue side of the  $2^3S_1 \rightarrow 2^3P_1$  transition at  $1034.31 \text{ \AA}$ , which means that it could scatter the UV light from the photosphere to a different wavelength. However, it is not clear that this will greatly affect the line ratio, as the scattering process does not generally destroy photons. The detailed effects of scattering by this transition could be assessed by modelling the radiative transfer in the wind at this wavelength range, but this is beyond the scope of this work.

### 2.3. The integrated ratio

In the preceding two subsections we calculated the radial dependence of the  $f/i$  ratio. Here we will calculate the  $f/i$  ratio integrated over an emitting volume that may span a wide range of radii. After all, for any realistic model of a stellar wind, we expect the X-ray emitting plasma to be distributed over a large range of radii (although it could be a small range of radii for a coronal model). We cannot directly observe the ratio as a function of radius, but only the overall ratio, or the ratio as a function of the observed Doppler shift.

We make the simple assumptions that the emissivity of the X-ray emitting plasma scales as the wind density squared above some onset radius. This is the same set of assumptions as the model of Owocki & Cohen (2001), with the two additional simplifications that there is no continuum absorption and that there is no radial variation in the X-ray filling factor. These approximations are not unreasonable, considering the low characteristic optical depths and the radial dependence of the filling factor reported by Kramer et al. (2003) for fits to line profiles in the *Chandra* HETGS spectrum of  $\zeta$  Pup, especially for high  $Z$ , where the optical depths are expected to be smallest.

To calculate the integrated strength of the forbidden and intercombination lines, we weight the integrand with the normalized (radially dependent) strength of each line.<sup>2</sup> The weights are

$$f(u) = G \frac{\mathcal{R}(u)}{1 + \mathcal{R}(u)} \quad (7)$$

and

$$i(u) = G \frac{1}{1 + \mathcal{R}(u)}. \quad (8)$$

Here  $u \equiv R_*/r$  is the inverse radial coordinate. We have introduced  $G \equiv (for + int)/res$  to ensure that the weighting factors are properly normalized relative to the resonance line; we will discuss this in more detail in the next section. The radial dependence of  $\mathcal{R}(u)$  was discussed in the previous sections (cf. Equation 3).

The integrated ratio is then

$$\bar{\mathcal{R}}(u_0) = \frac{\int dV \eta_f}{\int dV \eta_i} \quad (9)$$

where  $\eta_{f,i}$  are the emissivities of the forbidden and intercombination lines. The integrals are

$$\int dV \eta_{f,i} \propto \int_{R_0}^{\infty} \Omega(r) r^2 dr \rho^2(r) f, i(r) \propto \int_0^{u_0} \frac{du \Omega(u)}{w^2(u)} f, i(u) \quad (10)$$

where we have used  $\rho(u) \propto u^2/w(u)$ .  $\Omega(u) = 2\pi(1 + \sqrt{1 - u^2})$  is the solid angle visible by the observer (i.e. not obscured by the stellar core).  $w(u) = v(u)/v_{\infty} = (1 - u)^{\beta}$  is the scaled velocity; we take  $\beta = 1$  as a convenient approximation, as discussed in the following section.  $R_0$  is the onset radius for X-ray emission, and  $u_0 = R_*/R_0$  is its inverse. The He-like line strength weights  $f, i(u)$  are given by Equations 7 and 8, respectively.

In Figure 2, the solid lines show the integrated  $f/i$  ratio as a function of  $u_0$  for Mg XI in  $\zeta$  Ori. The integrated ratio is very similar for both the averaged flux (black solid line) and unaveraged (red solid line) flux cases. Since it is much simpler to consider only a single value of photospheric UV flux and because it agrees well with the more detailed treatment, we do so in the rest of this paper. However, it should be noted that if one modeled the X-ray emission as arising near a single radius or Doppler shift, as might be appropriate for a coronal model, the actual photospheric flux (including absorption lines) would have to be included in the modeling.

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<sup>2</sup>We could instead express the integrated ratio as a single volume integral of the f-to-i ratio with a weighting term for the overall emissivity of the complex, but we feel that formalism we use here, of a ratio of two separate emissivity integrals, is more intuitive. However, the two methods are formally equivalent.

It is important to note that there are two separate physical effects being considered here: the first is the effect of using the actual photospheric spectrum instead of a wavelength average, and the second is the averaging of the  $\mathcal{R}$  ratio over a range of radii. What Figure 2 shows is that the first effect is not important if we include the second. However, when comparing the radius inferred from a localized model to the *minimum* radius inferred from the distributed model, it is crucial to realize that they are physically different quantities. The radius in a localized model can be taken literally as the characteristic location of the X-ray emitting plasma, but in the distributed model, the minimum radius is the smallest radius where there is X-ray emission; it can be interpreted physically as the shock onset radius.

In Figures 3,4,5, and 6, we show  $\mathcal{R}(u)$  and  $\overline{\mathcal{R}}(u_0)$  for all He-like ions observed in the four O stars we consider in this paper. These plots all assume an averaged value of the photospheric UV flux. For a given measured value of  $\mathcal{R}$ , there are substantial differences between the value of  $u_0$  derived assuming a distributed plasma and the value of  $u$  derived assuming a plasma dominated by one radius - that is,  $u_0$  is always larger than  $u$  for a single radius, as one would expect.

In Table 3 we compare our calculations using TLUSTY model stellar atmosphere fluxes to the same calculations using Kurucz (1979) fluxes, as in Waldron & Cassinelli (2001) and Cassinelli et al. (2001). We make the comparison for one key ion for each paper, both of which have their  $2^3S_1 \rightarrow 2^3P_J$  transition wavelengths in the Lyman continuum. We use  $\mathcal{R}_0$  values taken directly from the plots of Waldron & Cassinelli (2001) and Cassinelli et al. (2001). For most ions in these two papers,  $\mathcal{R}_0$  is taken from BDT, but for Si XIII, Waldron & Cassinelli (2001) use  $\mathcal{R}_0 = 2.85$ , while the BDT value is 2.51. The values of  $\mathcal{R}_0$  given in BDT are systematically higher than those in Porquet et al. (2001).

There are substantial differences between our calculations of  $\mathcal{R}_{ph}$  (the value of  $\mathcal{R}$  at the photosphere) and those of Waldron & Cassinelli (2001), Cassinelli et al. (2001), and Miller et al. (2002). These differences mainly arise from differences in the continuum flux of the photospheric models shortward of the Lyman edge; the TLUSTY models generally predict a factor of 2-3 more than the Kurucz models.

The combination of the different Lyman continua and  $\mathcal{R}_0$  values lead to substantially higher values of  $\mathcal{R}_{ph}$  for Si XIII and S XV in Waldron & Cassinelli (2001), Cassinelli et al. (2001), and Miller et al. (2002). This means that we would infer systematically larger radii than these authors, given the same measured value of  $\mathcal{R}$ .

Regardless of the differences between TLUSTY and Kurucz model atmospheres, there are substantial uncertainties in the Lyman flux of any model atmosphere; this part of the spectrum is generally inaccessible to observation, and the models' Lyman continua have not

been directly verified experimentally. In the two cases where early B stars have been directly observed in the Lyman continuum with *EUVE*, the fluxes have been roughly an order of magnitude above models (Cassinelli et al. 1995, 1996); however, it should be pointed out that these stars are significantly cooler than the O stars we are studying, so that their Lyman fluxes are more sensitive to changes in the temperature structure in the outer atmosphere. Furthermore, the effective temperature scale used for O stars in the past may be systematically too high (Martins, Schaerer, & Hillier 2002), which would also have more of an effect on the part of the spectrum shortward of the Lyman break. However, the effect of the uncertainty in the model Lyman continuum flux is significantly larger than the effect of the correction to the effective temperature scale.

#### 2.4. He-like line profiles

Although it may sometimes be easier to measure the  $f/i$  ratio directly and compare it to a calculation for the ratio as a function of distance from the star, it is potentially much more powerful to calculate line profiles including the radial dependence of the line ratio and compare these to the data. The expression for the line profile derived in OC is

$$L_x = C \int_0^{u_x} du \frac{f_X(u)}{w^3(u)} e^{-\tau(u,x)} \quad (11)$$

In this expression, the volume filling factor of X-ray emitting plasma is  $f_X(u) \propto u^q$ , while  $x$  refers to the velocity-scaled dimensionless Doppler-shift parameter.  $\tau(u,x)$  is the optical depth along the line of sight to the observer, which is usually written as the product of a geometrical integral,  $t(u,x)$ , and a dimensionless constant,  $\tau_* = \frac{\kappa \dot{M}}{4\pi v_\infty R_*}$ , the characteristic optical depth. It should be noted that the expression for the optical depth is only analytic for integral values of the velocity law index  $\beta$ ; otherwise it must be evaluated numerically. Because the expression for  $L_x$  must also be evaluated numerically, it is preferable to take  $\beta$  to be an integer in order to avoid a multidimensional integral.  $\beta = 1$  is the best integer approximation for most O stars (see, e.g., Puls et al. (2006) for models that include clumping).

To account for the relative line strengths of the triplet, we simply multiply the integrand with the weighting factors  $f(u) = G \frac{\mathcal{R}(u)}{1+\mathcal{R}(u)}$  or  $i(u) = G \frac{1}{1+\mathcal{R}(u)}$ . This normalizes the forbidden and intercombination lines to the resonance line, which may be calculated using the above expression with no modification. If it is desirable to normalize the sum of all three weighting factors to unity, one may divide them by  $1+G$ . In this work we have assumed that  $G$  does not vary with radius. Although  $G$  does depend on temperature, the variation is not strong, and the X-ray emitting plasma is likely multiphase. If there is any variation in the line

profile shapes caused by a radial dependence in  $G$ , it is not likely to be detectable except with data of very high statistical quality.

In comparison with the integrated plots presented in the previous section, a line profile with  $\tau_* > 0$  has a higher  $\mathcal{R}$  ratio than one with no absorption, given the same value of  $u_0$ . This is because the forbidden line is only formed farther out where absorption is less, while the intercombination line is mainly formed close to the star, where absorption is greater. Nonzero positive values of  $q$  cause  $\mathcal{R}$  to go down, because relatively more emission comes from close to the star, while negative values cause  $\mathcal{R}$  to go up.

In comparison with normal line profiles, the intercombination line has weaker wings, as it becomes much weaker far away from the star. On the other hand, the forbidden line is relatively flat topped; because of photoexcitation, the profile appears as if it has a larger effective value of  $R_0$  than the resonance line.

The addition of the radial dependence of  $f/i$  ratio to the OC profile model has the appealing property of enforcing self-consistency between the radial dependences of the Doppler profile and the  $f/i$  ratio. Also, although it does make the quite reasonable assumption that the X-ray emitting plasma follows the same  $\beta$ -velocity law as the wind, it is not tied to any particular heating mechanism.

In the next section, we use this model to fit Chandra HETGS spectra of four O stars.

### 3. Data reduction and analysis

In this section we fit He-like triplets in the *Chandra* HETGS data of four O stars:  $\zeta$  Pup,  $\zeta$  Ori,  $\iota$  Ori, and  $\delta$  Ori. We only fit Mg XI, Si XIII, and for  $\zeta$  Pup S XV. This is because Ne IX and lower  $Z$  He-like species generally have  $\mathcal{R} < 0.2$  in O stars and therefore do not contain significant information in the line ratio.

#### 3.1. Data processing

Primary data products were obtained from the *Chandra* data archive and processed using standard CIAO routines outlined in the CIAO grating spectroscopy threads.<sup>3</sup> The versions used were CIAO 3.1 and CALDB 2.28. The spectral fitting was done with XSPEC 11.3.1. The  $C$  statistic (Cash 1979) is used instead of  $\chi^2$  because of the low number of counts per

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<sup>3</sup><http://cxc.harvard.edu/ciao/threads/gspec.html>

bin. For  $\zeta$  Ori and  $\iota$  Ori the data were split into two observations each, which were fit simultaneously. Emission lines were fit over a wavelength range of  $(\lambda_r(1 - v_\infty/c) - \Delta\lambda, \lambda_f(1 + v_\infty/c) + \Delta\lambda)$ , where  $\Delta\lambda$  is the resolution of MEG at that wavelength. This range was chosen to include the entire emission line, but at the same time to prevent the quality of the continuum fit from influencing the fit statistic for the line. To get the continuum strength for a given line, we first fit it outside this range, but near the wavelength of the line.

Because the MEG has substantially more effective area than the HEG at longer wavelengths, we used only the MEG  $\pm 1$  order data for Si XIII in  $\zeta$  Pup and for Mg XI for all stars. For the S XV complex in  $\zeta$  Pup and the Si XIII complex in the other stars, the statistics are poorer, and the contribution of the HEG is significant, so we simultaneously fit both the HEG and MEG  $\pm 1$  order data. The MEG  $\pm 1$  order data for Si XIII in  $\zeta$  Ori are inconsistent, so we fit each of them separately; this inconsistency is discussed in more detail in the results subsection.

### 3.2. Fitting procedure

We use two different fitting procedures, depending on the number of counts in the triplet. For triplets with many counts (Mg XI for all stars, and Si XIII for  $\zeta$  Pup), we fit them with the He-like OC profile described in § 2.4. The fixed model parameters are the line rest wavelengths, the terminal velocity of the wind, the velocity law index  $\beta = 1$ , the unaltered  $f/i$  ratio  $\mathcal{R}_0$ , and the averaged photospheric UV strength. The fit parameters from the profile model are  $q$ ,  $\tau_*$ , and  $u_0$ , in addition to the  $G$  ratio and the overall normalization. The four fit parameters other than normalization are fit on a grid with spacing 0.2 for  $q$  and  $\tau_*$ , and spacing 0.05 for  $u_0$  and  $G$ .

For lines with few counts (S XV for  $\zeta$  Pup and Si XIII for the other stars), we fit a three Gaussian model to prevent overinterpretation. Rather than using three individual Gaussians, which would have three separate normalizations, we use a model with parameters  $G$ ,  $\mathcal{R}$ , the overall normalization, and the velocity width, which is taken to be the same for all the lines in a given complex. This avoids fitting problems due to covariance in individual line normalizations, which can be a problem in blended line complexes. It also allows us to directly measure the line ratios and their errors, which are the quantities of interest. We fit the parameters on a grid with spacing  $2 \times 10^{-3}$  for  $\sigma_v$ , 0.2 for  $\mathcal{R}$ , and 0.1 or 0.2 for  $G$ . We interpret the results of these multi-Gaussian fits using the integrated ratio formalism described in § 2.3 and shown in Figures 3-6.

In all cases we add a continuum component to approximate bremsstrahlung emission.

This is represented by a power law of index 2 with normalization chosen to fit the continuum near the line. Care is taken to avoid including moderately weak spectral lines in the continuum fit. A power law of index 2 is not necessarily appropriate for the continuum in general, but over a sufficiently short range in wavelength, any reasonable continuum shape is statistically indistinguishable. An index of 2 is chosen because this gives a flat continuum when  $F_\lambda$  is plotted versus wavelength.

We do not expect any other strong lines to contaminate our line fits. Mg XII Ly  $\gamma$  is at approximately the same wavelength as the Si XIII forbidden line, but even in  $\zeta$  Ori, where Si XIII is relatively weak, the strength of Mg XII Ly  $\gamma$  expected based on the strength of Mg XII Ly  $\alpha$  is not enough to affect our measurements significantly.

#### 4. Results

The results of the fits are summarized in Tables 4 and 5. The fits are plotted with the data in Figures 7-21. The data have been rebinned for presentation purposes in some of the plots, but in all cases the data were fit without rebinning.

We show two-parameter confidence interval plots for the profile fit to Mg XI for  $\zeta$  Pup in Figure 22. These confidence intervals are qualitatively representative of our results for all the line complexes; they demonstrate that there is a moderate correlation of the parameters  $q$  and  $u_0$  in the profile fits, and that the other parameters are not strongly correlated. The correlation in  $q$  and  $u_0$  is expected, as both parameters influence the radial distribution of plasma, and therefore both the  $f/i$  ratio and the profile width.

The goodness of fit is tested by comparing the fit statistic to that obtained from Monte Carlo simulations from the model. The percentage of 1000 realizations having  $C$  less than the data is given in the tables of results. These percentages can be thought of as rejection probabilities.

The helium-like line profile fits generally are adequate to explain the data; they are all formally statistically acceptable. The fact that the fits can simultaneously account for the profile shape and the  $f/i$  ratio indicates that the values of  $u_0$  obtained are not an artifact of the profile model. In other words, we can explain both the line ratios and profile shapes with a single model for the radial distribution of X-ray emitting plasma.

The fit parameters obtained for the He-like profile fits are generally consistent with those obtained in Kramer et al. (2003) and Cohen et al. (2006) from non-helium-like line profile fits. The  $\mathcal{R}$  ratios for the helium-like line profile fits are also consistent with those

measured in Kahn et al. (2001), Waldron & Cassinelli (2001), Cassinelli et al. (2001), and Miller et al. (2002). The values of  $u_0$  for all four stars fall in the range  $0.6 < u_0 < 0.8$ , or  $1.25 < R_0 < 1.67$ . This is substantially closer to the star than the values of  $u$  inferred in Kahn et al. (2001), Waldron & Cassinelli (2001), and Cassinelli et al. (2001) from  $f/i$  ratios. This reflects the difference between assuming a single radius of formation as opposed to a distribution of radii.

We now consider the lower signal-to-noise complexes, which we fit with Gaussians. For the Si XIII lines in  $\iota$  Ori and  $\delta$  Ori, the  $\mathcal{R}$  ratio is not strongly constrained, and in both cases the data are consistent with  $\mathcal{R} = \mathcal{R}_0$ . The goodness of fit is formally acceptable in both cases. If anything, it is surprising that the  $\mathcal{R}$  ratio is not slightly lower in both cases, considering the values of  $u_0$  measured for the Mg XI lines.

The  $\mathcal{R}$  ratio measured in S XV in  $\zeta$  Pup is equivalent to a value of  $R_0 = 1.1_{-0.1}^{+0.4}$ , based on Figure 3. The  $1\sigma$  upper limit to  $R_0$  is consistent with what is seen in other lines and with the expectations of hydrodynamic models of wind shocks (Feldmeier et al. 1997b; Runacres & Owocki 2002). The fit to these lines is formally acceptable.

The fit to the Si XIII complex of  $\zeta$  Ori is poor. Because the positive and negative first order MEG data look very different, we fit them separately in addition to the joint fit. These additional fits are shown in Figures 13 and 14. Part of the difference in appearance is a result of the Si XIII complex falling on a chip gap in the negative first order, which reduces the effective area and makes it uneven. However, even accounting for this there is a substantial difference in the fit results for the two orders, both for  $\mathcal{R}$  and for  $G$ . It is possible to get a satisfactory fit using only the positive first order MEG data, but fitting the negative first order by itself gives a poor fit. Because the negative first order data for this complex falls on a chip gap, cannot be fit well by a three Gaussian model, and has substantially fewer counts than the positive first order, we consider it to be unreliable.

In Table 6 we compare our fits for Si XIII in  $\zeta$  Ori and S XV in  $\zeta$  Pup to those of Waldron & Cassinelli (2001) and Cassinelli et al. (2001), respectively. There is not enough information in their original work to directly compare their best fit model to ours; they do not give the velocity broadenings or overall normalizations. We use their published values of  $\mathcal{R}$  and  $G$  and find the best fit parameters for velocity broadening and normalization. Waldron & Cassinelli (2001) do not present their measurements of  $G$ , but we infer from the temperature range they claim is allowed that they measure  $G$  in the range 0.8-2.0. We assume the best fit was in the middle of this range, or  $G = 1.4$ . In both cases, we also tried letting  $G$  be a free parameter, in order to test the validity of their  $\mathcal{R}$  measurements independently of any claims about  $G$ . For S XV in  $\zeta$  Pup, we found that the best fit occurs with a substantially different value of  $G$  than that reported by Cassinelli et al. (2001).

Our measurement of the  $\mathcal{R}$  ratio of Si XIII in  $\zeta$  Ori is significantly different than that of Waldron & Cassinelli (2001). Statistically, their best-fit measurement has a  $C$  value that is 11.7 greater than our best fit. For one interesting parameter, this is excluded at more than  $3\sigma$ . The reported value of  $\mathcal{R} = 1.2 \pm 0.5$  is also very different than our measured value of  $2.8 \pm 0.8$ . Two points should be reiterated: first, when fitting all the data, we do not get a statistically acceptable fit, but the positive first order MEG data can be well-fit, and this fit has an  $\mathcal{R}$  ratio which is comparable to the value we measure using all the data; furthermore, whether we use all the data or exclude the questionable negative first order MEG data from the fit, we get essentially the same result. Second, we are using essentially the same model as Waldron & Cassinelli (2001), but merely measure very different parameter values, even when fitting exactly the same data. This may stem from the fact that Waldron & Cassinelli (2001) used very early versions of the CIAO tools (J. P. Cassinelli, private communication).

Our measurement of the  $\mathcal{R}$  ratio of S XV in  $\zeta$  Pup is somewhat different than that of Cassinelli et al. (2001). We also found that the if we fix  $\mathcal{R}$  to the value they reported, the best fit value of  $G$  is substantially different than their measurement. Although their best fit model with  $\mathcal{R} = 0.61$  is not excluded at the  $1\sigma$  level, the model based on their measured value of  $G$  has a value of  $C$  which is greater than that of our best fit by 9.5, despite the fact that we both fit a three Gaussian model. Although we do not exclude their best-fit value of  $\mathcal{R}$  at  $1\sigma$ , it is also puzzling that our range of fit values should be significantly different from that of the previous work.

## 5. Discussion

We have used the  $f/i$  ratios of He-like triplets in conjunction with their line profiles to constrain the radial distribution of X-ray emitting plasma in O stars. Our results are consistent with the results of Kramer et al. (2003) and Cohen et al. (2006) in the sense that the spatial distribution we infer from  $f/i$  ratios (additionally constrained in some cases by line profile fitting) is consistent with these authors' results from fitting line profiles to high signal-to-noise individual lines.

Our results for Si XIII in  $\zeta$  Ori are different from the initial analysis which claimed that the location of the emitting plasma was extremely close to the star. These differences are due both to our assessment of the relative line fluxes and to our modeling of the line formation. Table 6 shows a comparison of our measurements and inferred radii of formation; we find that the Si XIII is at least 1.1 stellar radii above the photosphere ( $R_0/R_* = 2.1$ ). Part of the difference in inferred radii originates in our different calculations of the radial dependence of  $\mathcal{R}$ . This is illustrated in Figure 23, where we plot our calculations and measurements of

$\overline{\mathcal{R}}(u_0)$  and compare them to the calculations and measurements of  $\mathcal{R}(u)$  from Waldron & Cassinelli (2001). (It is important to note that the range of radii indicated on the plot by the thickened lines refers to that allowed by the statistical error in the measurement of  $\mathcal{R}$ , and not to a physical extent of the X-ray emitting plasma). We also show what our inferred radius of formation would be if we inferred a single radius from our measured value of  $\mathcal{R}$  instead of an onset radius  $R_0$  in a distributed model (assuming that an averaged value of the photospheric UV flux could be used). This is intended to make it clear that the major sources of disagreement are the actual  $\mathcal{R}$  measurements and the UV fluxes of the adopted model atmospheres. In fact, even taking the reported upper limit on  $R$  (of 1.7) from WC2001, and assuming a single radius of formation (dash-dot curve in Figure 23), our analysis shows that the formation radius is consistent with values larger than  $2R_*$ . Although we also assume a spatial distribution of X-ray emitting plasma, this does not contribute to the new, larger formation radii.

We make a similar comparison with the earlier results (Cassinelli et al. 2001) for S XV for  $\zeta$  Pup in Table 6 and Figure 24. In this case the measured range of allowed values of  $\mathcal{R}$  is different but overlapping. The different measured range of  $\mathcal{R}$  combined with a somewhat higher model photospheric UV flux leads us to infer a minimum radius of formation as large as  $1.5R_*$ ; however the allowed range of minimum radii extends down to nearly the photosphere, in agreement with the results of Cassinelli et al. (2001). The upper range of allowed minimum radii is reasonable in the context of stellar wind models for X-ray-emitting plasma formation, but the lower range is certainly not. While the difference between our measurements and calculations and those of Cassinelli et al. (2001) is not great, it is enough to allow that the S XV emission could reasonably be produced in a wind shock model.

These results obviate the need for any kind of two-component model for the origin of X-ray emission in O stars, as suggested by Waldron & Cassinelli (2001), Cassinelli et al. (2001), and Mullan & Waldron (2006). For the Si XIII line in  $\zeta$  Ori the range of acceptable minimum radii of formation we infer are quite reasonable in the wind-shock paradigm. For the S XV line in  $\zeta$  Pup, the upper end of the range of acceptable minimum radii of formation we infer is acceptable in the wind-shock paradigm, although the lower end of the range is not. Taken together, we can say that the wind-shock paradigm is consistent with these data; we do not exclude the possibility that S XV in  $\zeta$  Pup is formed very close to the star or is formed in a process outside of the wind-shock paradigm, but we do not require this. We note that numerical simulations of the line-driven instability show that large shock velocities, and therefore hot plasma, occur quite deep in the wind, almost as soon as the damping effects of the diffuse radiation field are overcome by the onset of the instability growth (Runacres & Owocki 2002). While hybrid wind-coronal mechanisms are not excluded by the data, there is nothing in the X-ray spectral data that requires such complex models, and the principle of

Occam’s razor leads us to suggest that it is more reasonable to assume a wind shock origin for all X-rays from the O stars we are studying, if it is possible to explain the data this way. Another argument against inferring extremely small formation radii for these two ions is the lack of any evidence, either from line profiles or from  $f/i$  ratios, of the presence of emission from lower ion stages at these very small radii, as would be expected from the rapid radiative cooling of plasma containing S XV or Si XIII at the densities expected this far down in the wind.

It should be noted that there is one other claim in the literature of an anomalously low  $f/i$  ratio measurement requiring an X-ray production mechanism outside of the standard wind shock paradigm. Waldron et al. (2004) find evidence for this in their analysis of the X-ray spectrum of Cyg OB2 8A; in this case the basis for their claim is emission from S XV and Ar XVII. However, these ions’  $2^3S_1 \rightarrow 2^3P_J$  transitions are in the Lyman continuum, where results are very sensitive to model atmosphere uncertainties, so the inferred radii are subject to substantial uncertainties. Furthermore, the data have very low signal-to-noise.

The characteristic optical depths we measure from profile fits are substantially smaller than one would expect, given the published mass-loss rates. Detailed calculations of the expected values of  $\tau_*$  are beyond the scope of this paper, but it is safe to say that we would expect to see characteristic optical depths at least of order a few at 9 Å; our measurements for Mg XI give  $\tau_* = 1$  for  $\zeta$  Pup, and less for the other stars. However, Si XIII and Mg XI give poorer constraints on the optical-depth/mass-loss-rate discrepancy than longer wavelength lines, such as O VIII and N VII Lyman  $\alpha$ , where the photoelectric absorption cross-section per unit mass is higher, so that  $\tau_*$  is larger and produces a more asymmetric profile.

Waldron & Cassinelli (2001), Cassinelli et al. (2001), and Miller et al. (2002) compare the radii they infer from measurements of  $f/i$  ratios in He-like triplets to the radii of optical depth unity,  $R_1$ , for the wavelength at which that He-like ion emits. These values of  $R_1$  were calculated using mass-loss rates from the literature and assumed a smooth wind density. They claim that the inferred radii correspond roughly to  $R_1$ , so that we are observing plasma at the closest point to the star where we can see it. Kahn et al. (2001) make a similar conjecture. Table 7 compares the values of  $R_1$  from these papers to those derived using the methodology of this paper. Several lines show evidence for emission from inside the predicted  $R_1$ . This is in agreement with the low values of  $\tau_*$  we have measured, as well as the measurements of Kramer et al. (2003) and Cohen et al. (2006). There is now mounting evidence from analysis of unsaturated UV line profiles that the literature mass-loss rates of O stars may be too high by at least a factor of a few (Massa et al. 2003; Hillier et al. 2003; Bouret et al. 2005; Fullerton et al. 2006). In addition, porosity may reduce the effective X-ray optical depths of O star winds (Feldmeier et al. 2003; Oskinova et al. 2004, 2006;

Owocki & Cohen 2006).

## 6. Conclusions

We have investigated the effect of a radially distributed plasma on the forbidden-to-intercombination line ratio in helium-like triplets, as well as variations in the exciting photospheric flux as a function of Doppler shift throughout the wind. We find that the fact that the plasma is likely distributed over a range of radii and Doppler shifts allows us to use an averaged value of the photospheric continuum instead of accounting for it in detail. We also find that the value of  $R_0$  derived assuming a distribution of radii is substantially smaller than the value of  $R$  derived assuming a single radius.

We have used the  $f/i$  ratio of helium-like triplets to constrain the radial distribution of X-ray emitting plasma in four O-type stars. We find that the minimum radius of emission is typically  $0.6 < u_0 < 0.8$ , or  $1.25 < R_0/R_* < 1.67$  with the emission extending beyond this initial radius with either a constant filling factor or one that increases slightly with radius. This is consistent with the results of line profile fits using the model of Owocki & Cohen (2001) (Kramer et al. 2003; Cohen et al. 2006). However, some of the minimum radii of formation are well inside the radius of optical depth unity calculated using the mass-loss rates in the literature, implying that either the effective opacities are lower (e.g. due to porosity effects Feldmeier et al. 2003; Oskinova et al. 2004, 2006; Owocki & Cohen 2006) or the mass-loss rates are lower than the literature values (Massa et al. 2003; Hillier et al. 2003; Bouret et al. 2005; Fullerton et al. 2006) or both. We also measure low values of the characteristic optical depth  $\tau_*$  compared to what one would expect based on the literature mass-loss rates, which is consistent with the same conclusions.

We find that there is no evidence for anomalously low  $f/i$  ratios in high- $Z$  species. Our measurements do not require X-ray emission originating from too close to the star to have sufficiently strong shocks, nor do we need to posit the existence of a magnetically confined corona. This conclusion is based partly on different measured values of  $f/i$  ratios and partly on higher photospheric UV fluxes on the blue side of the Lyman edge in the more recent TLUSTY model spectra.

We have fit He-like emission line complexes with profile models that simultaneously account for profile shapes and line ratios. These models constrain the radial distribution of plasma both through the line ratio and the profile parameters  $u_0$  and  $q$ . We find that they are capable of producing good fits to the data, showing that the information contained in the line ratios and profile shapes are mutually consistent.

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Table 1. Parameters adopted for He-like triplets

Ion	$f (2^3S_1 \rightarrow 2^3P_J)$ <sup>a</sup>	$\phi_c$ (s <sup>-1</sup> ) <sup>b</sup>	$\mathcal{R}_0$ <sup>c</sup>	$G(T_{max})$ <sup>c</sup>
S XV	0.0507	9.16e5	2.0	...
Si XIII	0.0562	2.39e5	2.3	0.68
Mg XI	0.0647	4.86e4	2.7	0.71
Ne IX	0.0700	7.73e3	3.1	0.74
O VII	0.0975	7.32e2	3.7	0.90
N VI	0.1136	1.83e2	5.3	0.88

<sup>a</sup>Oscillator strengths are from CHIANTI (Dere et al. 1997; Young et al. 2003).

<sup>b</sup> $\phi_c$  are from Blumenthal, Drake, & Tucker (1972).

<sup>c</sup> $\mathcal{R}_0$  and  $G(T_{max})$  are from Porquet et al. (2001), except S XV, which is from Blumenthal, Drake, & Tucker (1972).

Table 2. Adopted stellar parameters

Star	Spectral type <sup>a</sup>	$T_{eff}$ (kK) <sup>b</sup>	$\log g$ (cm s <sup>-2</sup> ) <sup>b</sup>	$v_\infty$ (km s <sup>-1</sup> ) <sup>c</sup>
$\zeta$ Pup	O4 I	42.5	3.75	2485
$\zeta$ Ori	O9.5 I	30.0	3.25	1860
$\iota$ Ori	O9 III	35.0	3.50	2195
$\delta$ Ori	O9.5 II	32.5	3.25	1995

<sup>a</sup>Spectral types are given for reference and are taken from the Garmany values reported in Table 1 of Lamers & Leitherer (1993).

<sup>b</sup>Effective temperatures and surface gravities are the values on the TLUSTY O star grid that are the closest approximations to the values used in Lamers & Leitherer (1993).

<sup>c</sup>Terminal velocities are taken from Prinja, Barlow, & Howarth (1990).

Table 3. Comparison of He-like ratio calculations

		$\frac{\overline{H_\nu}}{E}$ <sup>b</sup>	$P$ <sup>c</sup>	$\mathcal{R}_{ph}/\mathcal{R}_0$	$\mathcal{R}_0$ <sup>d</sup>	$\mathcal{R}_{ph}$ <sup>e</sup>
$\zeta$ Ori	Si XIII	this work	1.97	3.09	0.244	2.3
		WC01 <sup>a</sup>	0.633	0.993	0.502	2.85
$\zeta$ Pup	S XV	this work	8.71	3.21	0.238	2.0
		C01 <sup>a</sup>	4.95	1.82	0.355	2.04
						0.72

<sup>a</sup>We used Kurucz model atmospheres to reproduce these authors' calculations. We assumed that  $\zeta$  Pup was represented by a model with  $T_{eff} = 40\text{kK}$  and  $\log g = 4.0$  and  $\zeta$  Ori by a model with  $T_{eff} = 30\text{kK}$  and  $\log g = 3.5$ .

<sup>b</sup>The photospheric UV flux,  $\frac{\overline{H_\nu}}{E}$ , is given in units of  $10^7$  photons  $\text{cm}^{-2} \text{s}^{-1} \text{Hz}^{-1}$ .

<sup>c</sup> $P \equiv \phi_*/\phi_c$  is discussed in Equations 3 and 4.

<sup>d</sup>For WC01 and C01 we used the  $\mathcal{R}_0$  values shown on their plots.

<sup>e</sup>Our calculations for  $\mathcal{R}_{ph}$  (which is the value of  $\mathcal{R}$  near the photosphere) using the Kurucz model atmospheres agree with the figures of WC01 and C01.

Note. — In this table we compare the adopted photospheric UV flux and the He-like triplet ratio calculations of Waldron & Cassinelli (2001) and Cassinelli et al. (2001) to those in this work.

Table 4. Parameters for He-like profile fits

Star	Ion	$q$	$\tau_*$	$u_0$	$R_0$ <sup>a</sup>	$G$	$\mathcal{R}$ <sup>b</sup>	Flux <sup>c</sup>	$C$	Bins	MC <sup>d</sup>
$\zeta$ Pup	Mg XI	$0.0^{+0.4}_{-0.2}$	$1.0^{+0.4}_{-0.4}$	$0.70^{+0.05}_{-0.05}$	1.43	$0.70^{+0.15}_{-0.10}$	0.41	$17.7^{+0.9}_{-0.9}$	135.3	136	39.1
	Si XIII	$0.0^{+0.6}_{-0.4}$	$0.6^{+0.4}_{-0.2}$	$0.70^{+0.05}_{-0.10}$	1.43	$1.05^{+0.15}_{-0.15}$	0.90	$11.9^{+0.7}_{-0.7}$	116.2	98	84.7
$\zeta$ Ori	Mg XI	$-0.4^{+1.0}_{-0.2}$	$0.2^{+0.2}_{-0.2}$	$0.6^{+0.10}_{-0.1*}$	1.67	$1.05^{+0.05*}_{-0.2}$	0.82	$6.5^{+0.5}_{-0.6}$	267.2	240	73.4
$\iota$ Ori	Mg XI	$-0.8^{+0.2}_{-0.0}$	$0.0^{+0.2}_{-0.0}$	$0.75^{+0.05}_{-0.10}$	1.33	$0.90^{+0.20*}_{-0.25}$	0.72	$3.5^{+0.5}_{-0.5}$	266.6	256	80.2
$\delta$ Ori	Mg XI	$-0.8^{+0.4}_{-0.0}$	$0.0^{+0.2}_{-0.0}$	$0.80^{+0.05}_{-0.10}$	1.25	$0.60^{+0.25}_{-0.10*}$	0.75	$4.0^{+0.5}_{-0.5}$	123.9	124	18.2

<sup>a</sup> $R_0$  is given in units of the stellar radius; it is calculated from  $R_0 = 1/u_0$ , and retains an extra digit to avoid rounding error.

<sup>b</sup> $\mathcal{R}$  is reported without an uncertainty because it is the value of the  $f/i$  ratio calculated by the best fit model.

<sup>c</sup>Flux is given in units of  $10^{-5}$  photons cm $^{-2}$  s $^{-1}$ .

<sup>d</sup>MC is the percentage of Monte Carlo realizations of the model having  $C$  less than the data does for that model.

Note. — Errors are  $2\sigma$ , or  $\Delta C = 4$  for one degree of freedom. Asterisks indicate parameters that were still within  $2\sigma$  at the edge of the fit range.

Table 5. Parameters for He-like Gaussian fits

Star	Ion	$\sigma_v/c(10^{-3})$	$\mathcal{R}$	$G$	Flux <sup>a</sup>	$C$	Bins	MC <sup>b</sup>	$R_0$
$\zeta$ Pup	S XV	$2.4^{+0.4}_{-0.4}$	$1.0^{+0.4}_{-0.4}$	$0.9^{+0.2}_{-0.2}$	$3.1^{+0.3}_{-0.3}$	191.2	216	78.4	$1.1^{+0.4}_{-0.1}$
$\zeta$ Ori	Si XIII <sup>c</sup>	$2.4^{+0.2}_{-0.0}$	$2.8 \pm 0.8$	$1.2^{+0.2}_{-0.1}$	$2.45 \pm 0.15$	432.1	496	97.9	$\geq 2.1$
		<sup>d</sup>	$2.0 \pm 0.2$	$\geq 2.8$	$0.9 \pm 0.2$	$2.4 \pm 0.4$	57.6	59	35.3
		<sup>e</sup>	$3.0^{+0.8}_{-0.6}$	$\geq 1.6$	$2.0^{+1.0*}_{-0.6}$	$2.4^{+0.6}_{-0.5}$	85.6	59	98.8
$\iota$ Ori	Si XIII	$2.8 \pm 0.4$	$2.8^{+0.6}_{-0.8}$	$1.6^{+0.4}_{-0.2}$	$1.54 \pm 0.24$	305.1	532	84.9	$\geq 3.2$
$\delta$ Ori	Si XIII	$1.2^{+0.0}_{-0.2}$	$2.2^{+1.0}_{-0.4}$	$0.7 \pm 0.1$	$1.88 \pm 0.16$	214.0	258	62.9	$\geq 2.2$

<sup>a</sup>Flux is in units of  $10^{-5}$  photons  $\text{cm}^{-2} \text{s}^{-1}$ .

<sup>b</sup>MC is the percentage of Monte Carlo realizations of the model having  $C$  less than the data does for that model.

<sup>c</sup>Combined fit to positive and negative first order HEG and MEG data.

<sup>d</sup>Fit to positive first order MEG data only.

<sup>e</sup>Fit to negative first order MEG data only.

Note. — Errors are  $1\sigma$ , or  $\Delta C = 1$ . Asterisks indicate parameters that were still within  $1\sigma$  at the edge of the fit range.

Table 6. Comparison of fit parameters

Star	Ion	$\sigma_v/c (10^{-3})$	$\mathcal{R}$	$G$	$C$	bins	$R_0, R$ <sup>d</sup>
This work	$\zeta$ Pup	S XV	2.4	1.0	0.9	191.2	216
			2.8	0.61	2.06	200.7	$< 1.2$
			2.4	0.61	0.9	192.0	
This work	$\zeta$ Ori	Si XIII	2.4	2.8	1.2	432.1	$\geq 2.1$
			2.2	1.2	1.4	443.8	$< 1.08$

<sup>a</sup>For C01a we used the published value of  $\mathcal{R}$  and  $G$ .

<sup>b</sup>For C01b we used the published value of  $\mathcal{R}$  and the best fit value for  $G$ .

<sup>c</sup>For WC01 the published value of  $G$  was the best fit, assuming their value of  $\mathcal{R}$ .

<sup>d</sup>For our work this column gives the inferred minimum radius of formation  $R_0$ , while for the previous work this column gives the inferred radius of formation  $R$ .

Note. — In this table we compare our fit parameters to those of Cassinelli et al. (2001) and Waldron & Cassinelli (2001) for two line complexes. In all cases, we used the best fit  $\sigma_v$  and normalization.

Table 7. Comparison of  $R_1$  to  $R_0$ 

Star	Ion	$R_1$	$R_0$ <sup>a</sup>
$\zeta$ Pup	Mg XI	2.5	$1.43 \pm 0.10$
	Ne IX	5	$< 2.5$
	O VII	4	$< 4$
$\zeta$ Ori	Mg XI	1.5	$1.67^{+0.33}_{-0.24}$
	Ne IX	2.8	$< 2.22$
	O VII	2.2	$< 2.85$
$\delta$ Ori	Mg XI	1.2	$1.25^{+0.18}_{-0.07}$
	Ne IX	2.1	$< 2.22$
	O VII	2.8	$< 3.33$

<sup>a</sup> $R_0$  is measured using an He-like line profile fit for Mg XI (see Table 4). Upper limits for O VII and Ne IX are derived from upper limits to the  $f/i$  ratio of  $\mathcal{R} < 0.1$  and  $\mathcal{R} < 0.2$ , respectively, which are taken to be representative for all three stars.

Note. — In this table we compare the radius of optical depth unity  $R_1$  calculated by Waldron & Cassinelli (2001), Cassinelli et al. (2001), and Miller et al. (2002) to measurements of  $R_0$ , the minimum onset radius for X-ray emission.

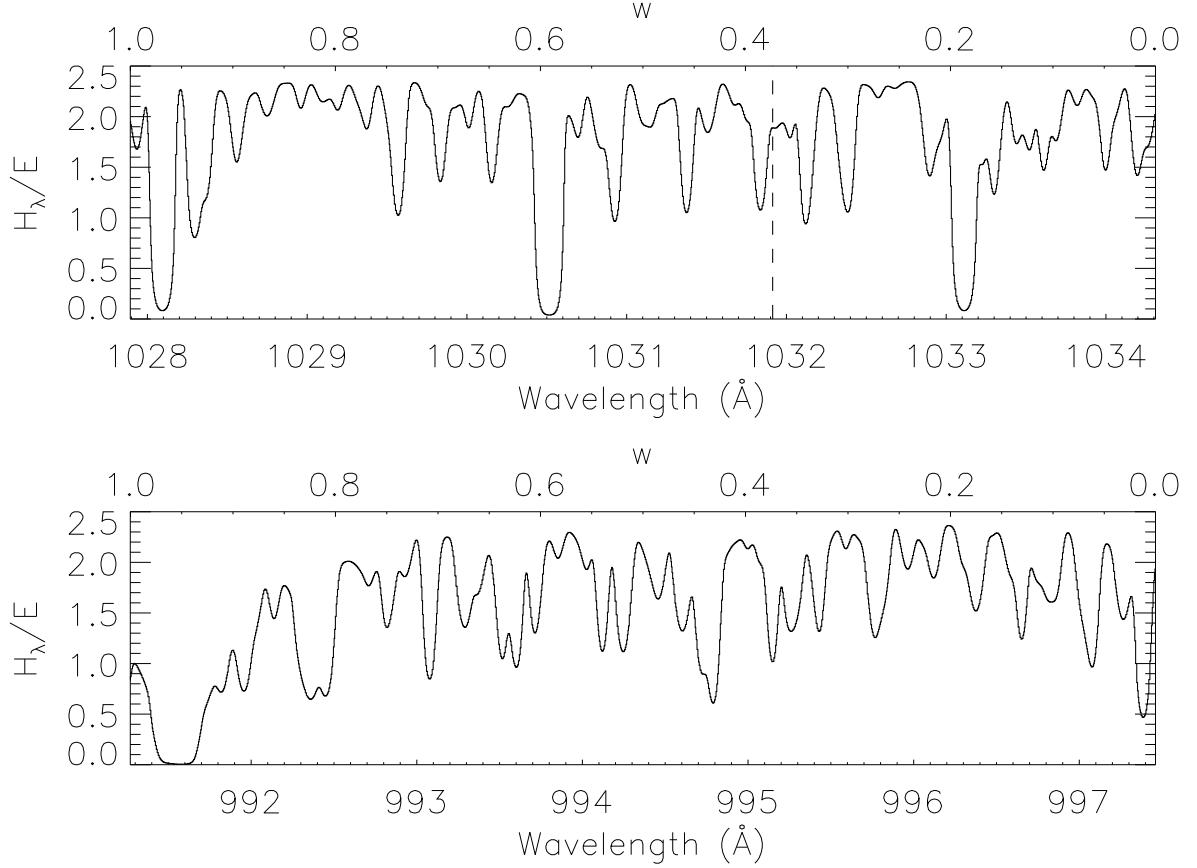


Fig. 1.— Model UV flux for  $\zeta$  Ori near the  $2^3S_1 \rightarrow 2^3P_{1,2}$  transitions of Mg XI ( $J = 1$  is on the top,  $J = 2$  on the bottom), plotted as a function of wavelength (bottom axis) and scaled stellar wind velocity,  $w(u) = v(u)/v_\infty$  (top axis). The flux is given in units of  $10^{20} \text{ photons cm}^{-2} \text{ s}^{-1} \text{\AA}^{-1}$ . The dashed line shows the rest wavelength of the O VI line at 1031.91  $\text{\AA}$ . For comparison, the average continuum flux we use for this ion and this star is 1.67, in the same units. The model flux is taken from the TLUSTY O star grid (Lanz & Hubeny 2003).

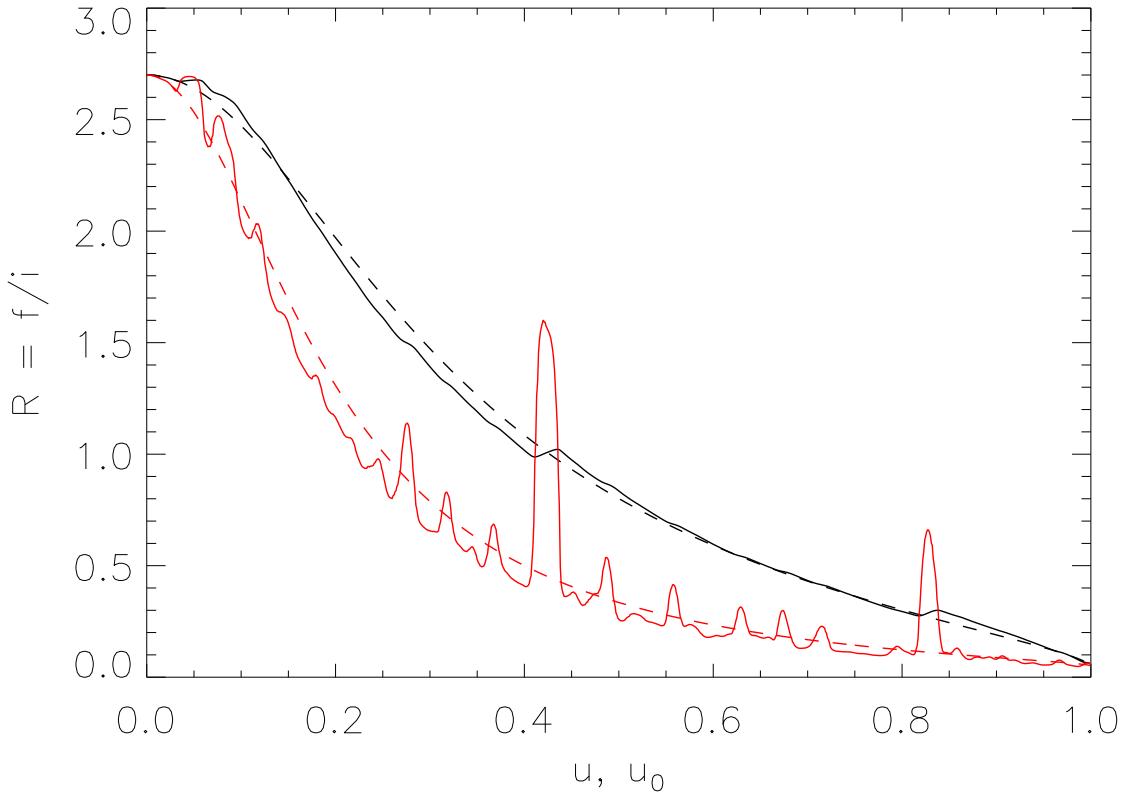


Fig. 2.— The  $f/i$  ratio for the Mg XI triplet of  $\zeta$  Ori plotted as a function of the inverse radial coordinate  $u = R_*/r$ . The solid lines are for the actual model photospheric UV flux, while the dashed lines are for an averaged value. The red lines denote the local radial dependence of  $\mathcal{R}(u)$  and the black lines show the integrated ratio  $\overline{\mathcal{R}}(u_0)$  observed for the whole star (see text). Note that  $u$  and  $u_0$  are not comparable physical quantities, since  $u$  corresponds to a single radius, which could be interpreted as a characteristic radius, while  $u_0$  corresponds to the *minimum* radius for the onset of X-ray emission. The solid lines include the effects of the photospheric UV flux for transitions to both the  $2^3P_1$  and  $2^3P_2$  states, although the  $2^3P_1$  state is far more important for Mg XI. The peaks in the red solid line correspond to the absorption lines in the top panel of Figure 1.

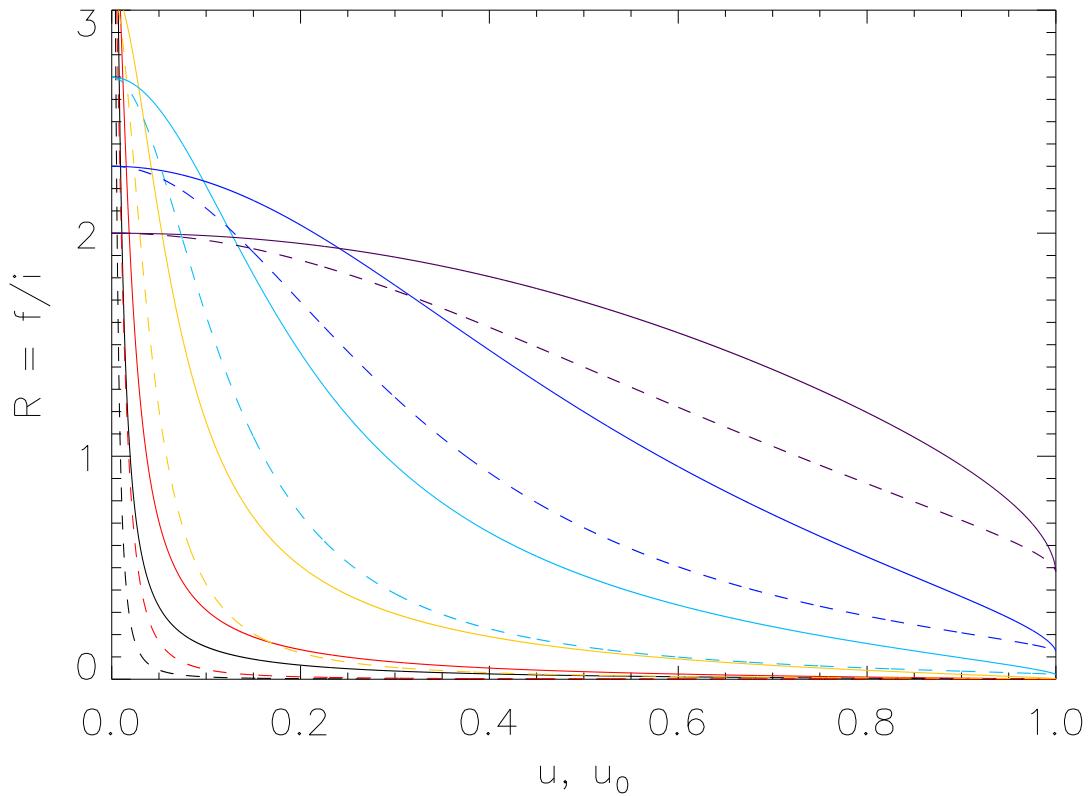


Fig. 3.— The  $f/i$  ratio for six He-like triplets observed in  $\zeta$  Pup. The dashed lines show the radial dependence of  $\mathcal{R}$ , while the solid lines show the dependence of the integrated ratio  $\bar{\mathcal{R}}$  on the inverse minimum radius  $u_0 = R_*/R_0$ . The colors are black for N VI, red for O VII, orange for Ne IX, green for Mg XI, blue for Si XIII, and purple for S XV.

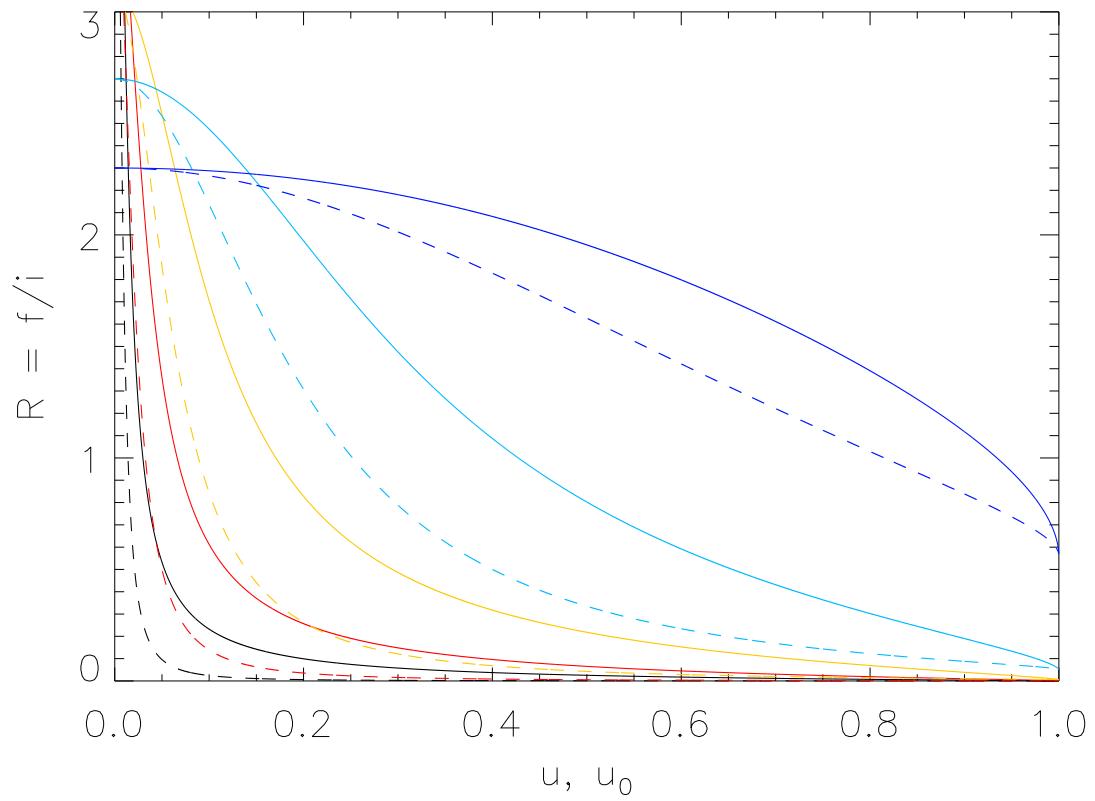


Fig. 4.— The  $f/i$  ratio for five He-like triplets observed in  $\zeta$  Ori. Scheme is as in Figure 3.

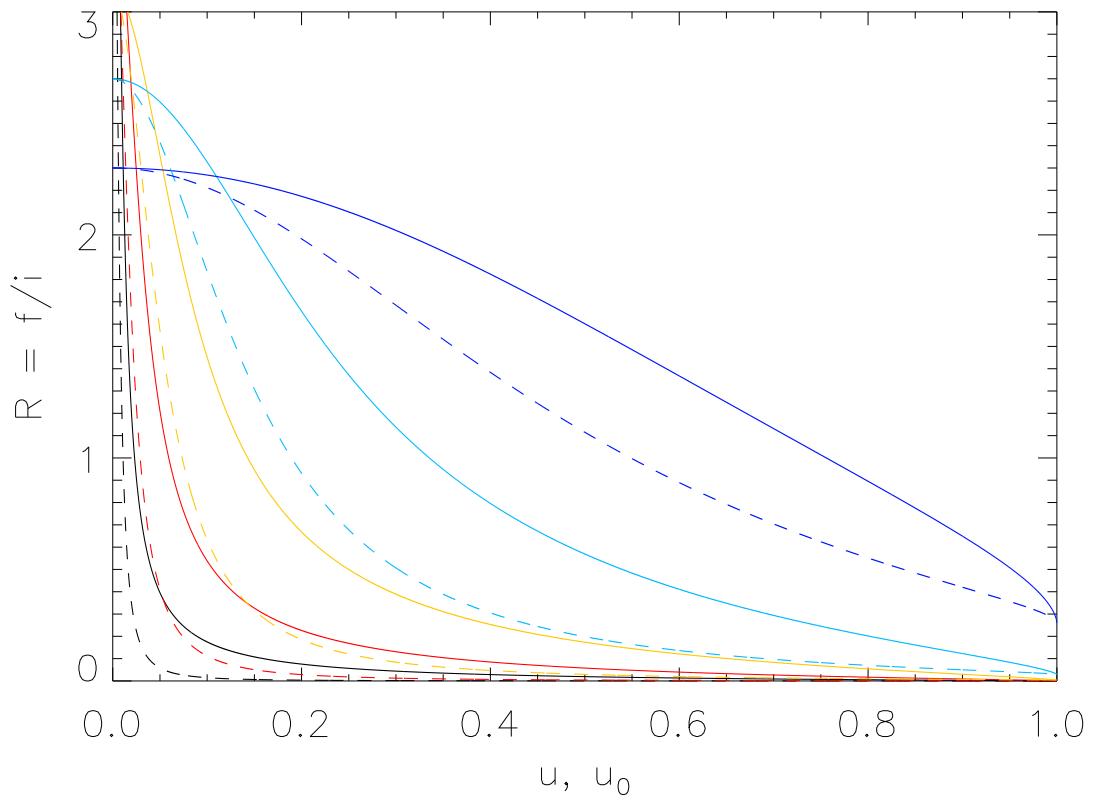


Fig. 5.— The  $f/i$  ratio for five He-like triplets observed in  $\iota$  Ori. Scheme is as in Figure 3.

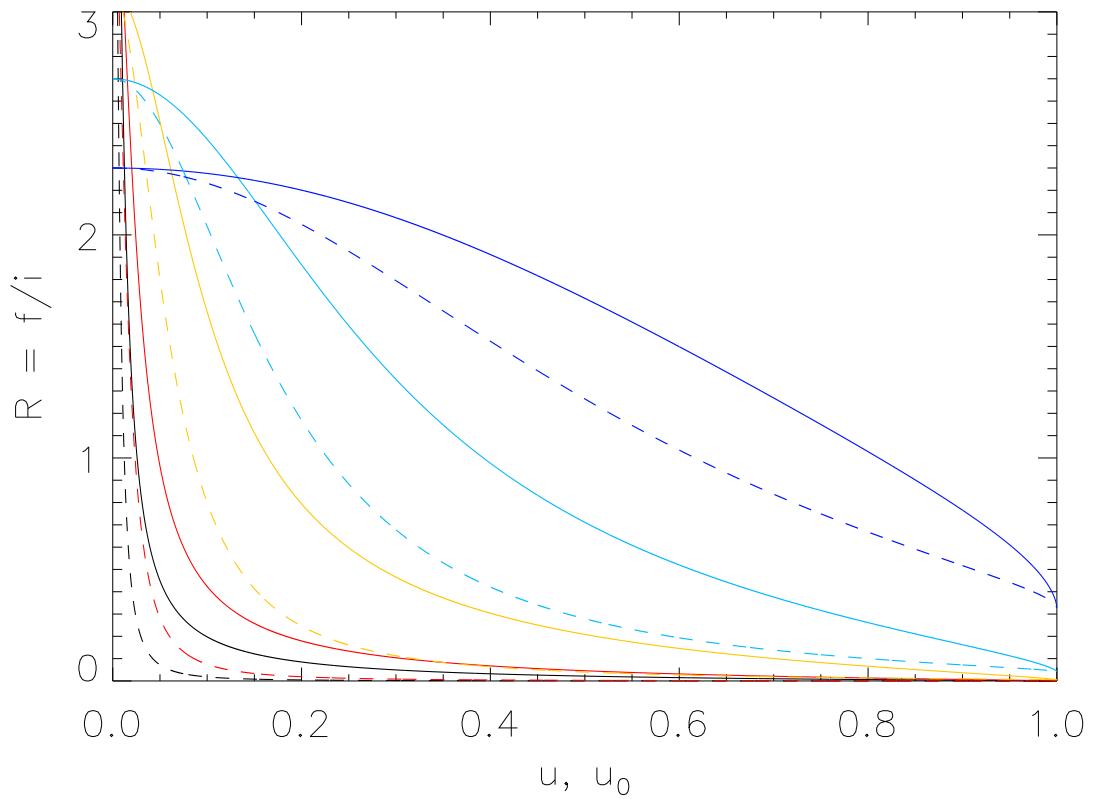


Fig. 6.— The  $f/i$  ratio for five He-like triplets observed in  $\delta$  Ori. Scheme is as in Figure 3.

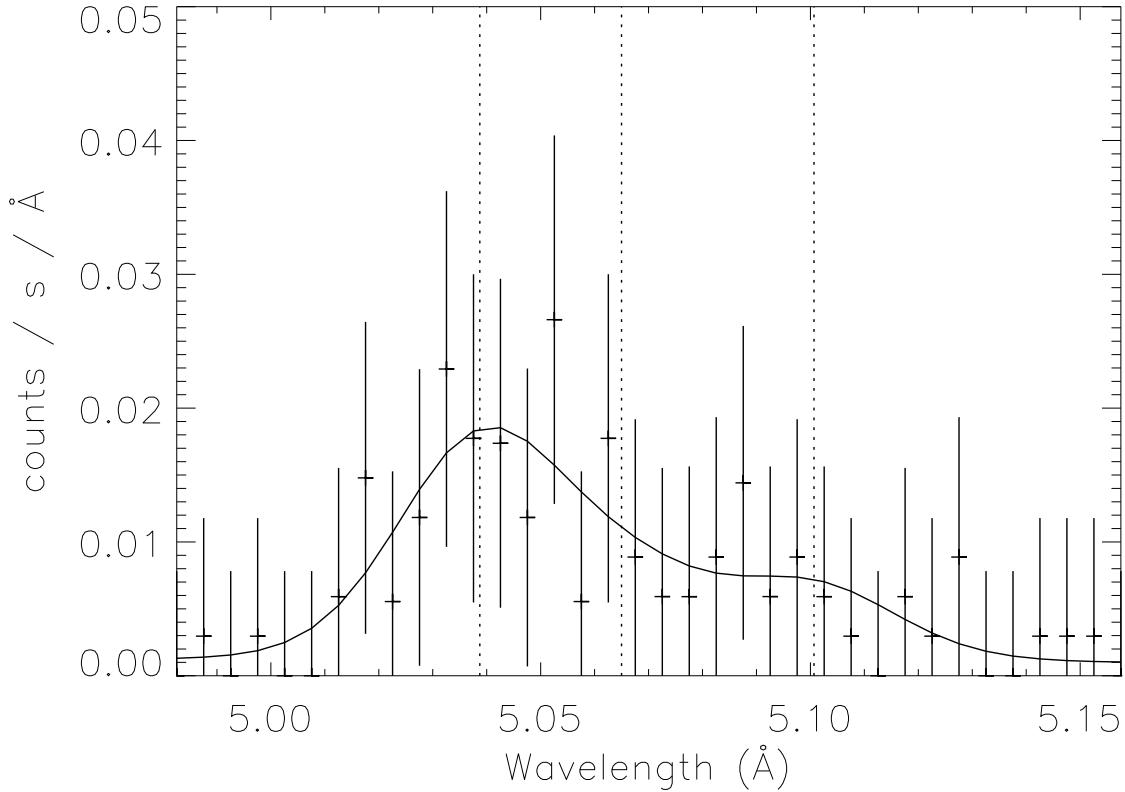


Fig. 7.— MEG data and best-fit model for S XV in  $\zeta$  Pup. The positive and negative first order data have been coadded. The data are shown with error bars, and the model is shown as a solid line. The rest wavelengths of the resonance, intercombination, and forbidden lines are shown with dotted lines. This scheme is used in all subsequent figures presenting the data. Except where stated explicitly, the plots of Gaussian fits show the joint best fit to both the HEG and MEG data, even though data from only one grating are presented at a time.

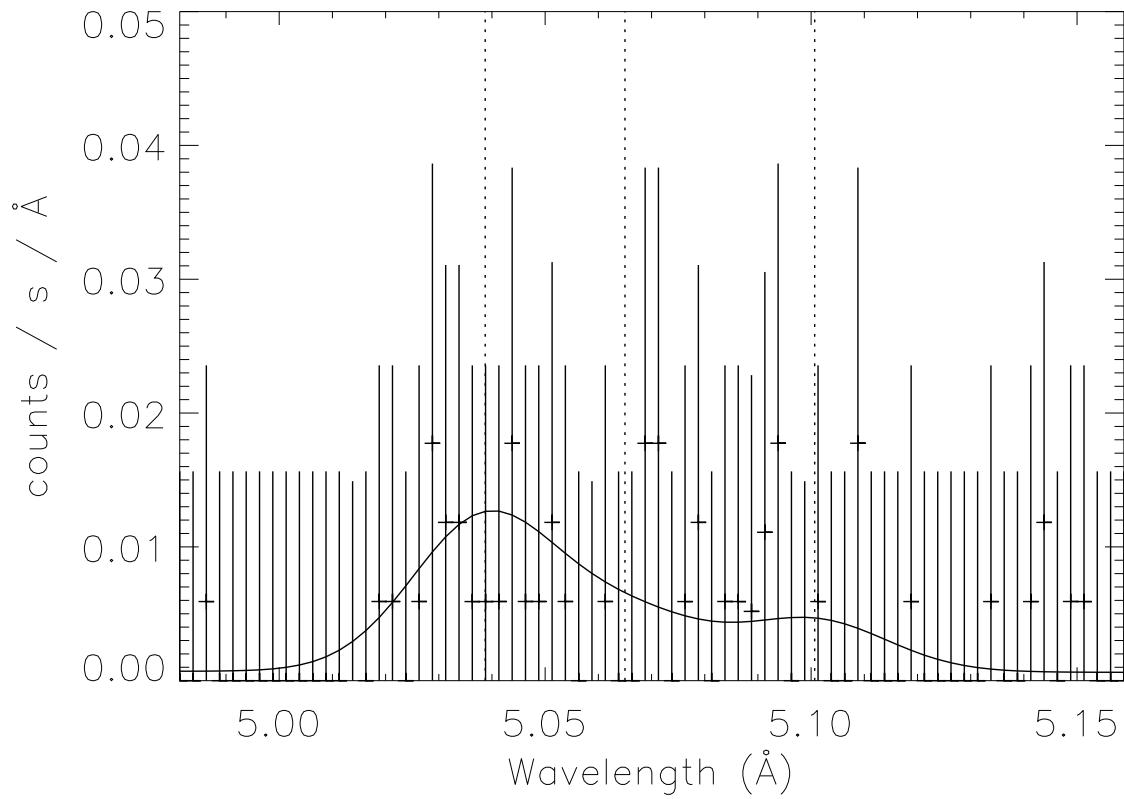


Fig. 8.— HEG data and best-fit model for S XV in  $\zeta$  Pup. The positive and negative first order data have been coadded.

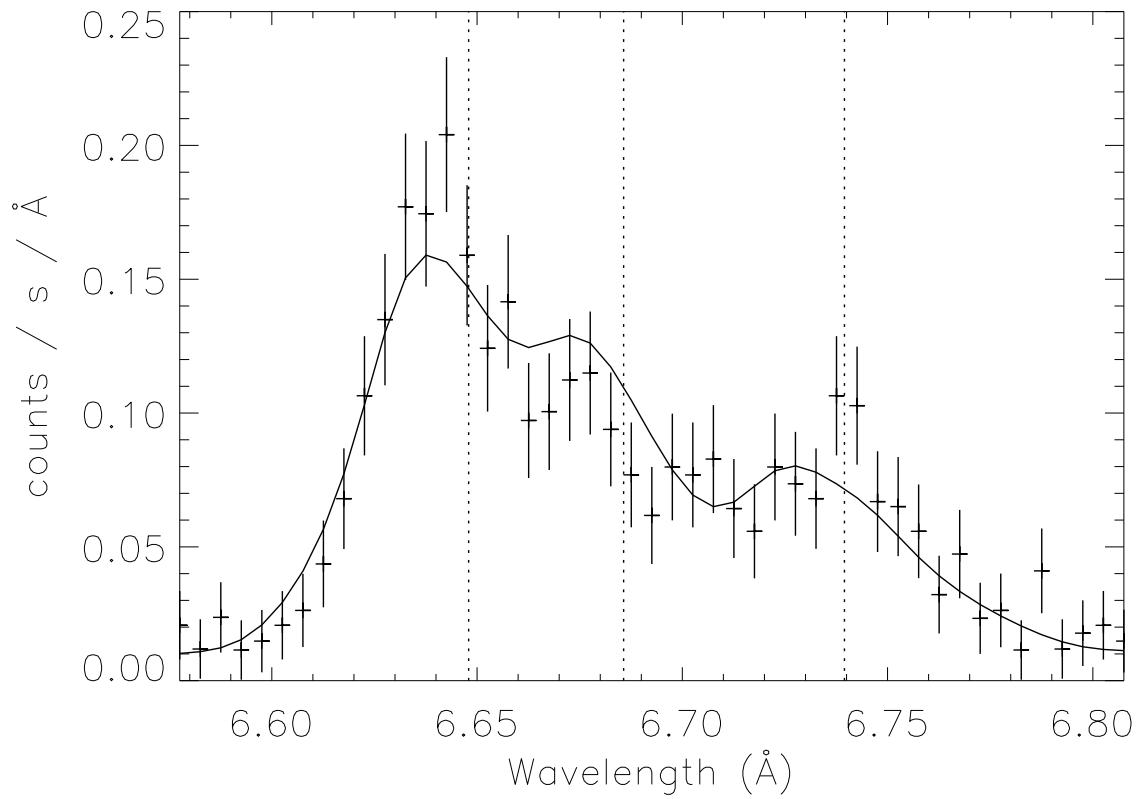


Fig. 9.— MEG data and best-fit model for Si XIII in  $\zeta$  Pup. The positive and negative first order data have been coadded.

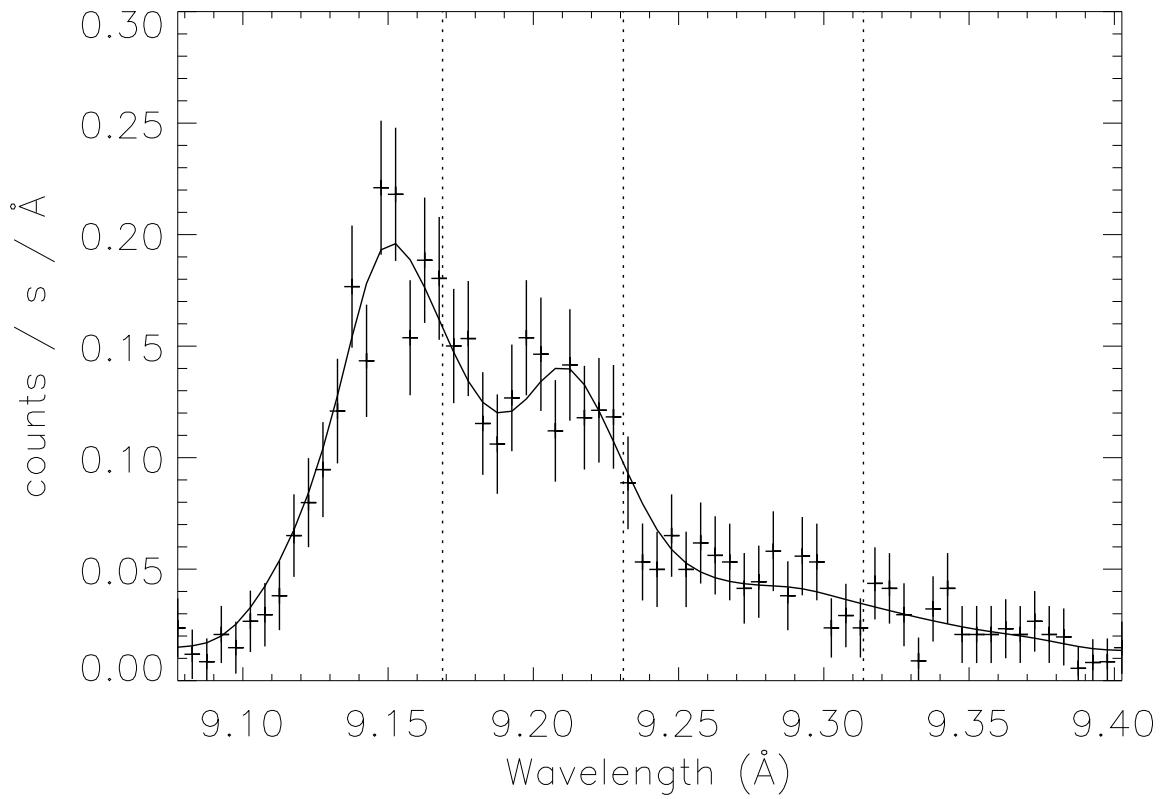


Fig. 10.— MEG data and best-fit model for Mg XI in  $\zeta$  Pup. The positive and negative first order data have been coadded.

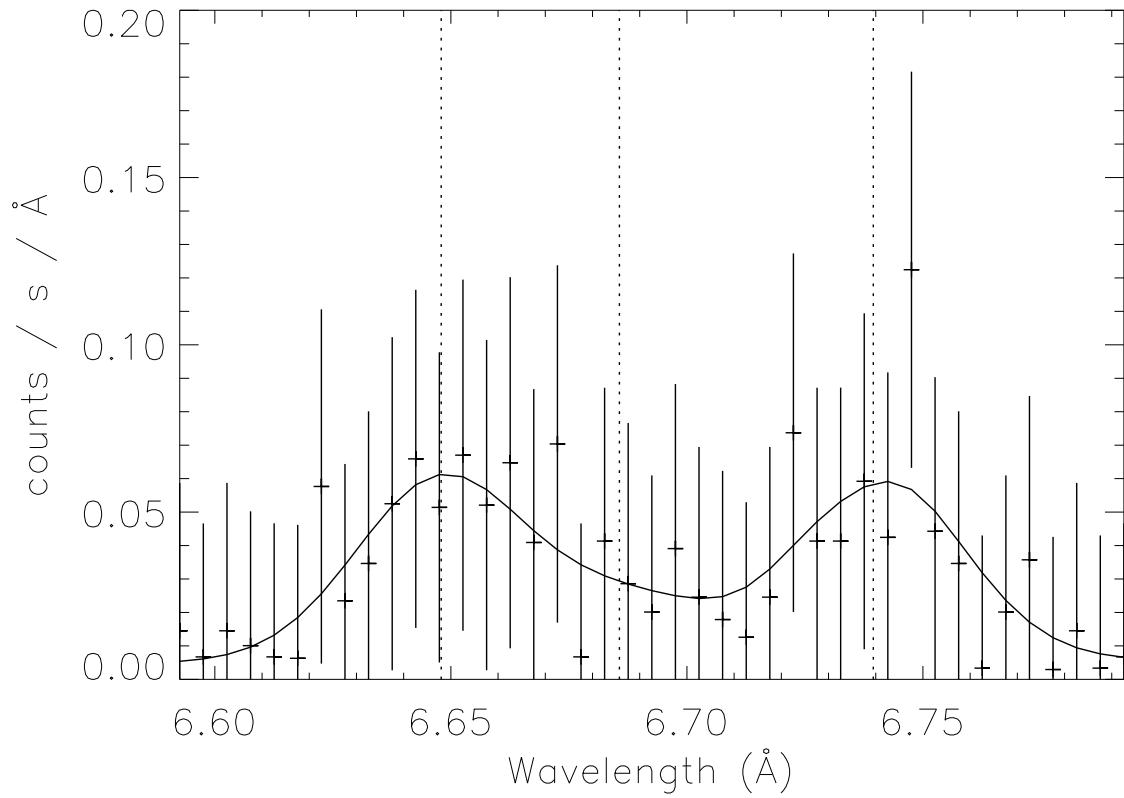


Fig. 11.— MEG data and best-fit model for Si XIII in  $\zeta$  Ori. The positive and negative first order data have been coadded. Figures 13 and 14 show the positive and negative first order MEG data separately.

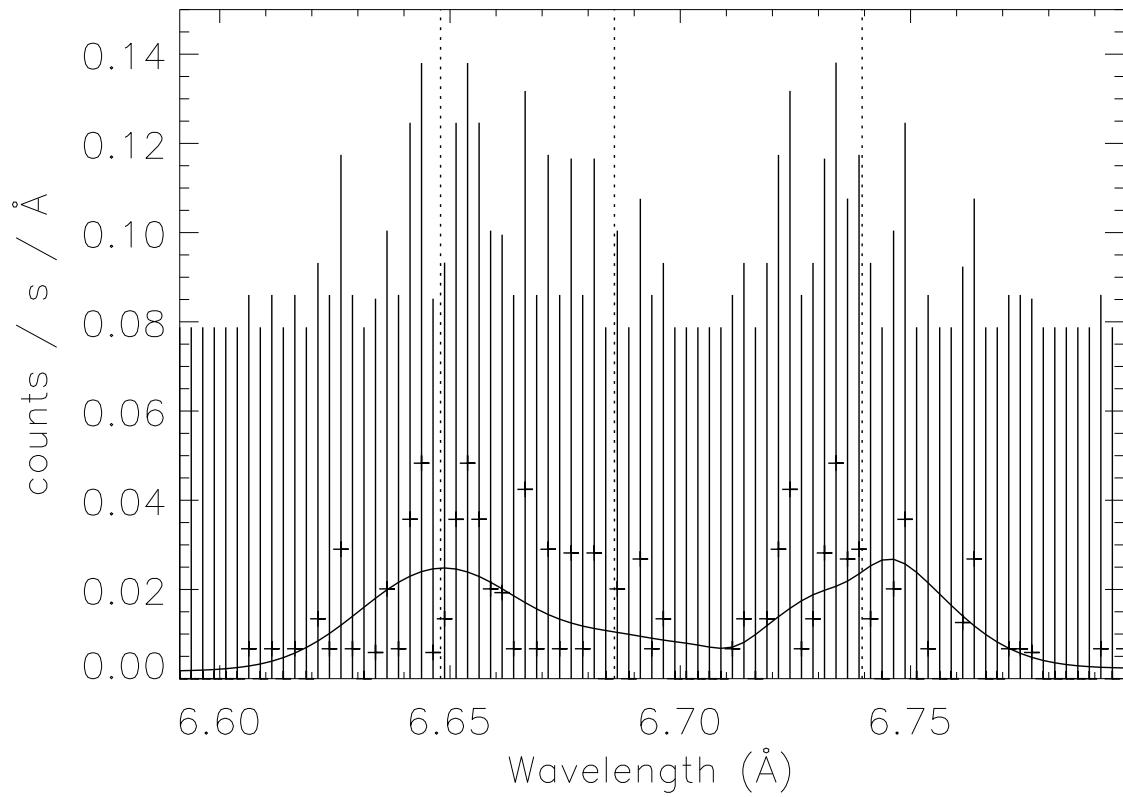


Fig. 12.— HEG data and best-fit model for Si XIII in  $\zeta$  Ori. The positive and negative first order data have been coadded.

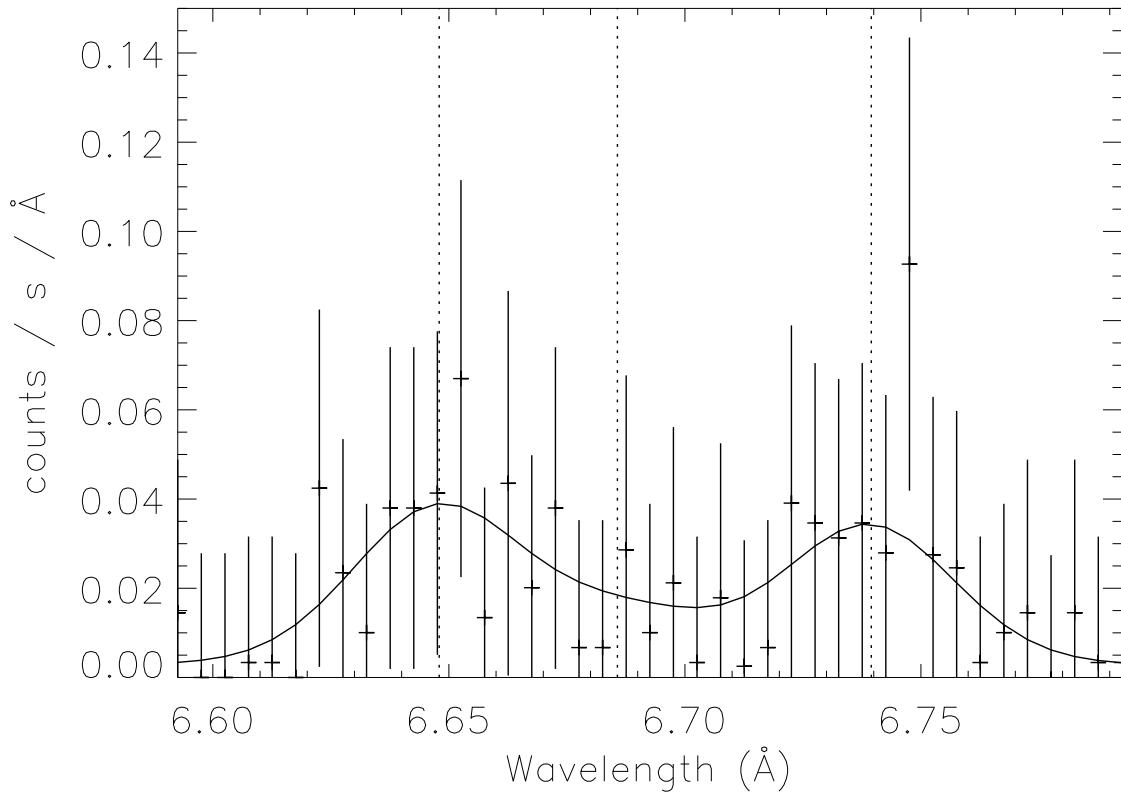


Fig. 13.— MEG positive first order data and best-fit model for Si XIII in  $\zeta$  Ori. The model is the best fit to *only* the positive first order data.

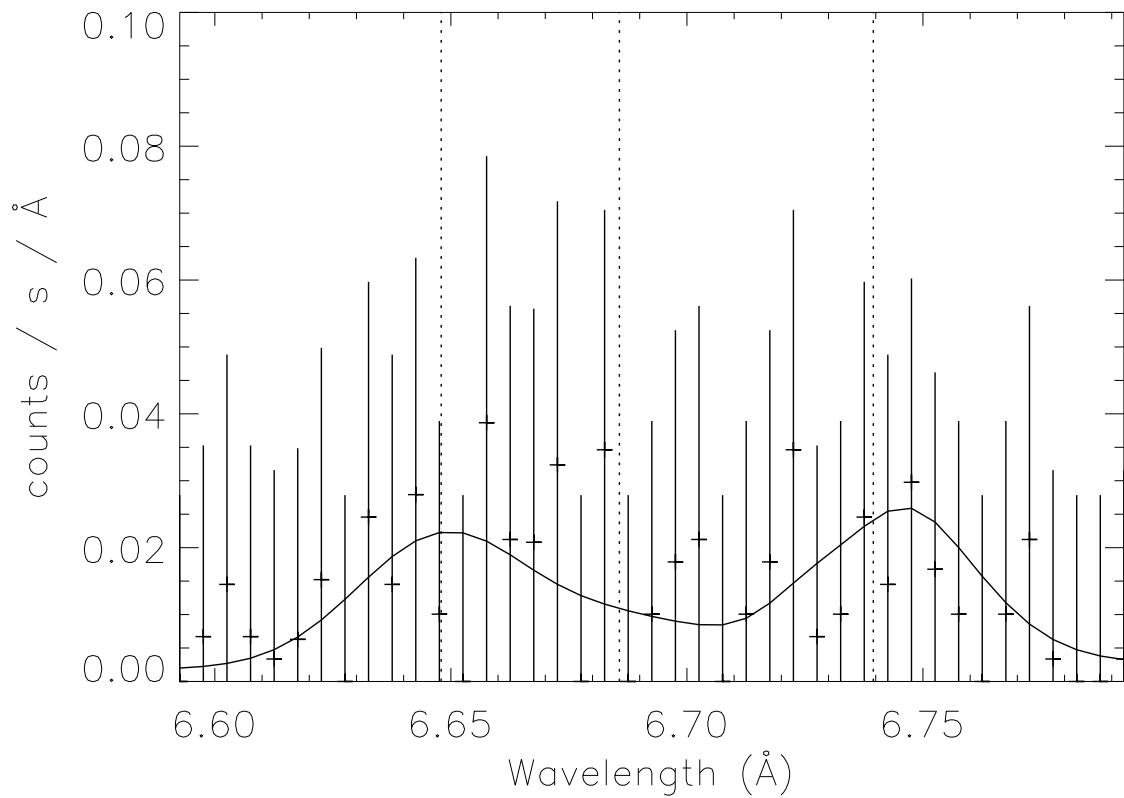


Fig. 14.— MEG negative first order data and best-fit model for Si XIII in  $\zeta$  Ori. The model is the best fit to *only* the negative first order data.

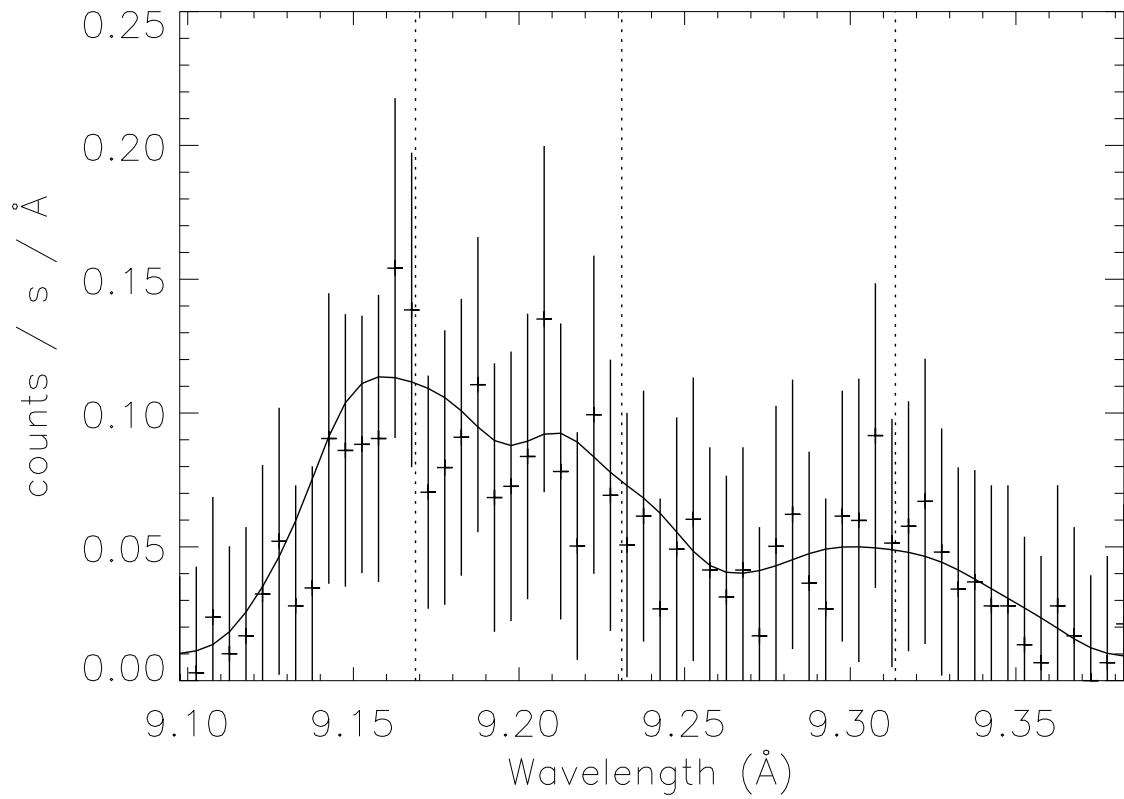


Fig. 15.— MEG data and best-fit model for Mg XI in  $\zeta$  Ori. The positive and negative first order data have been coadded.

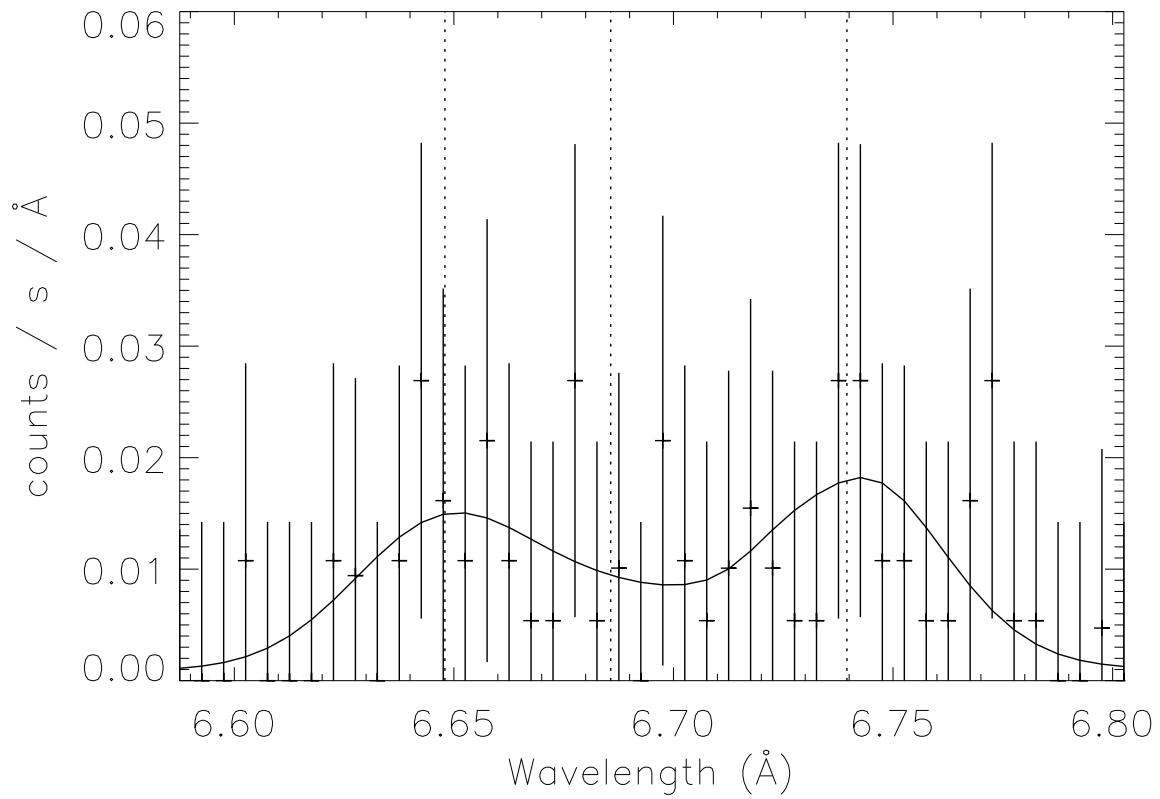


Fig. 16.— MEG data and best-fit model for Si XIII in  $\tau$  Ori. The positive and negative first order data have been coadded.

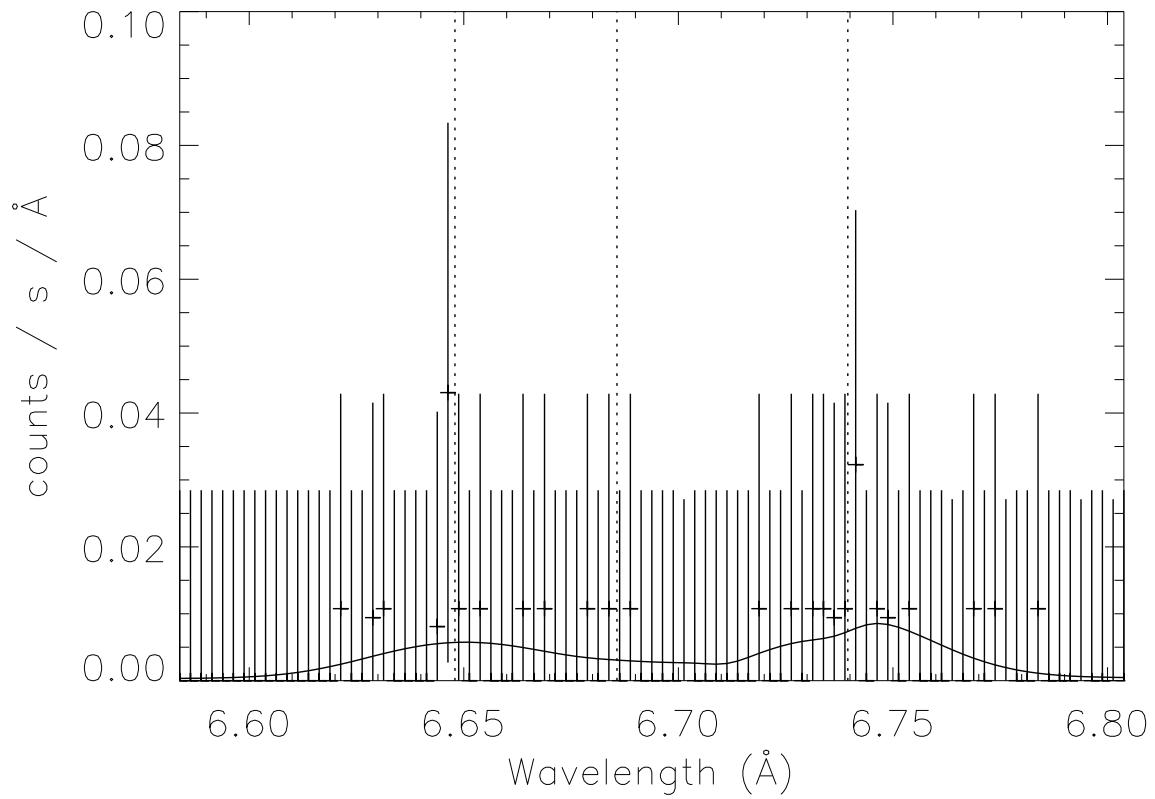


Fig. 17.— HEG data and best-fit model for Si XIII in  $\tau$  Ori. The positive and negative first order data have been coadded.

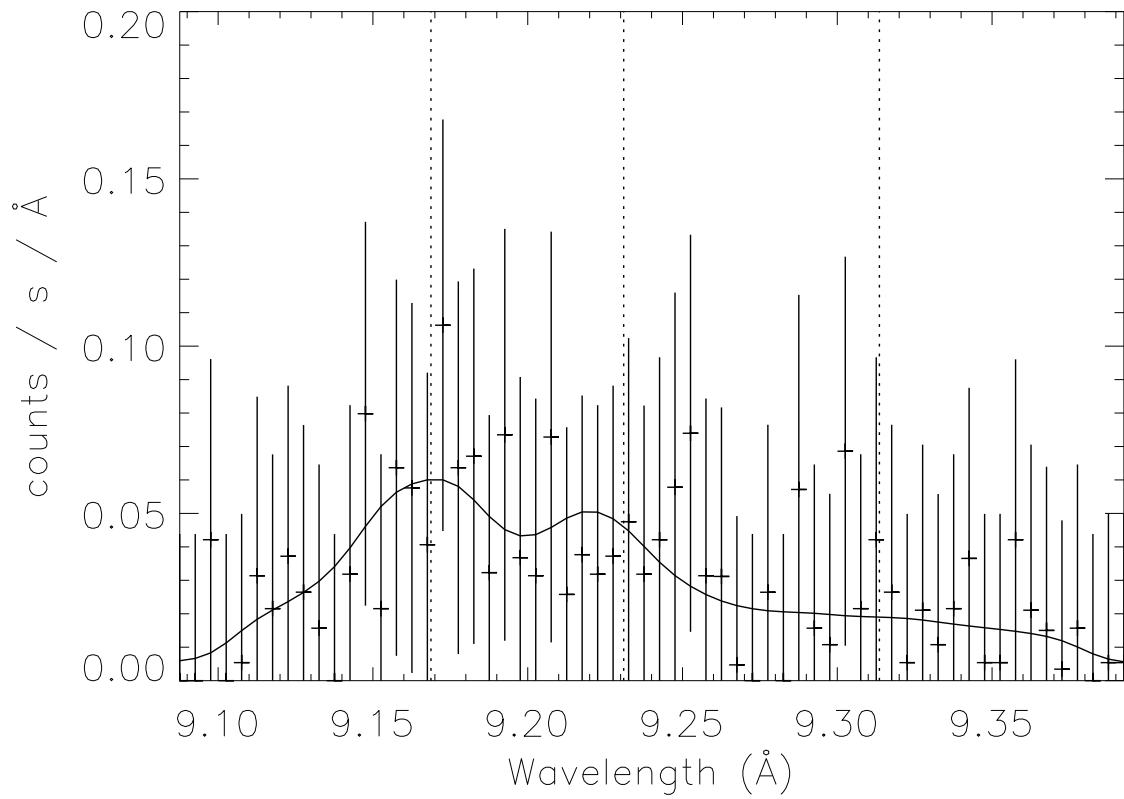


Fig. 18.— MEG data and best-fit model for Mg XI in  $\tau$  Ori. The positive and negative first order data have been coadded.

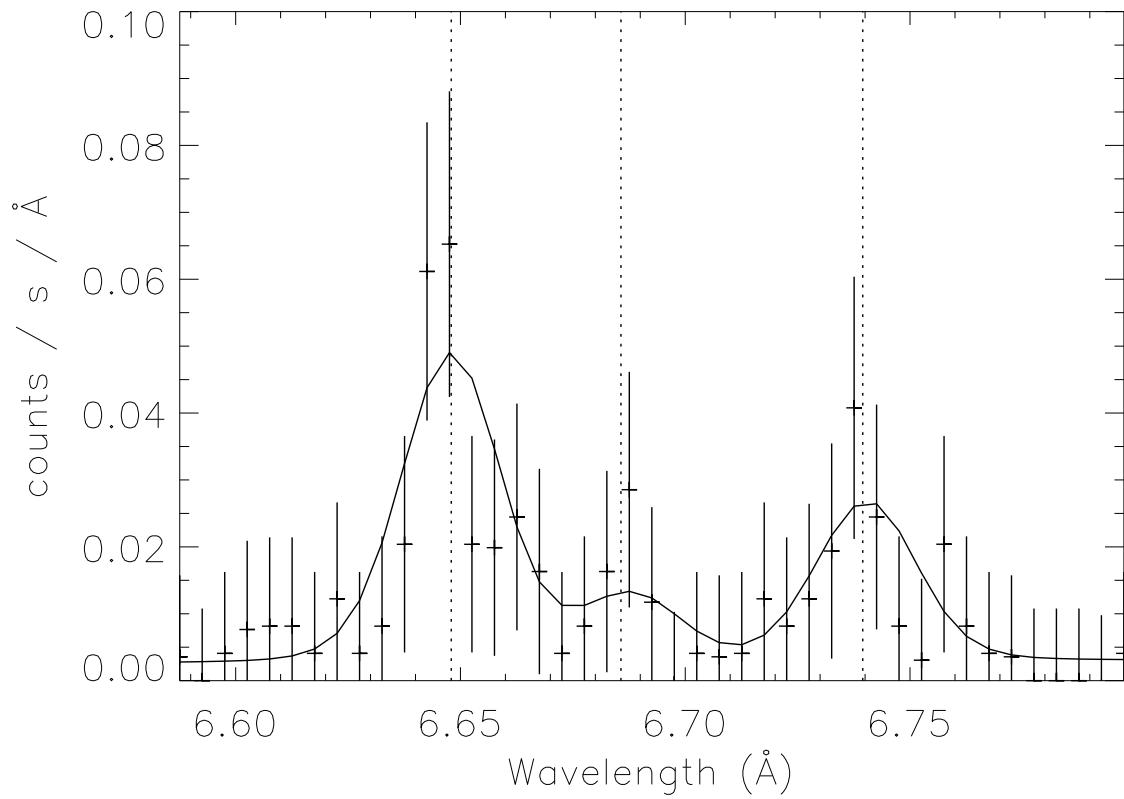


Fig. 19.— MEG data and best-fit model for Si XIII in  $\delta$  Ori. The positive and negative first order data have been coadded.

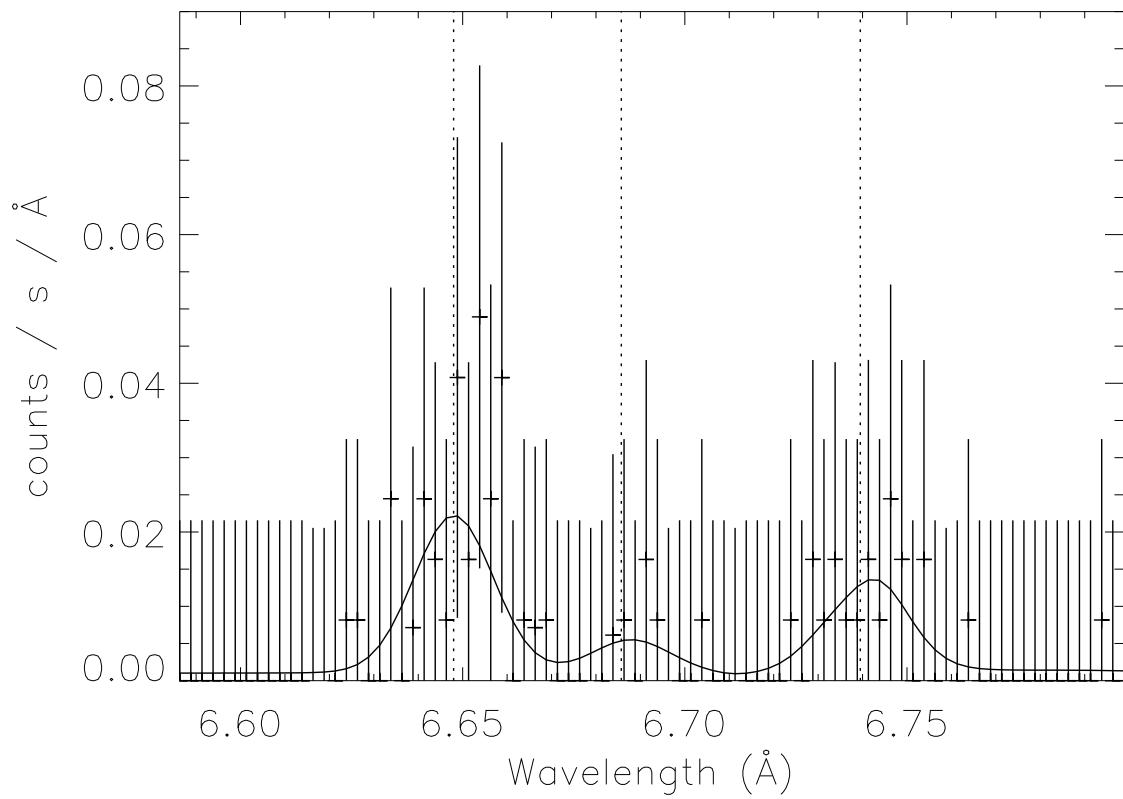


Fig. 20.— HEG data and best-fit model for Si XIII in  $\delta$  Ori. The positive and negative first order data have been coadded.

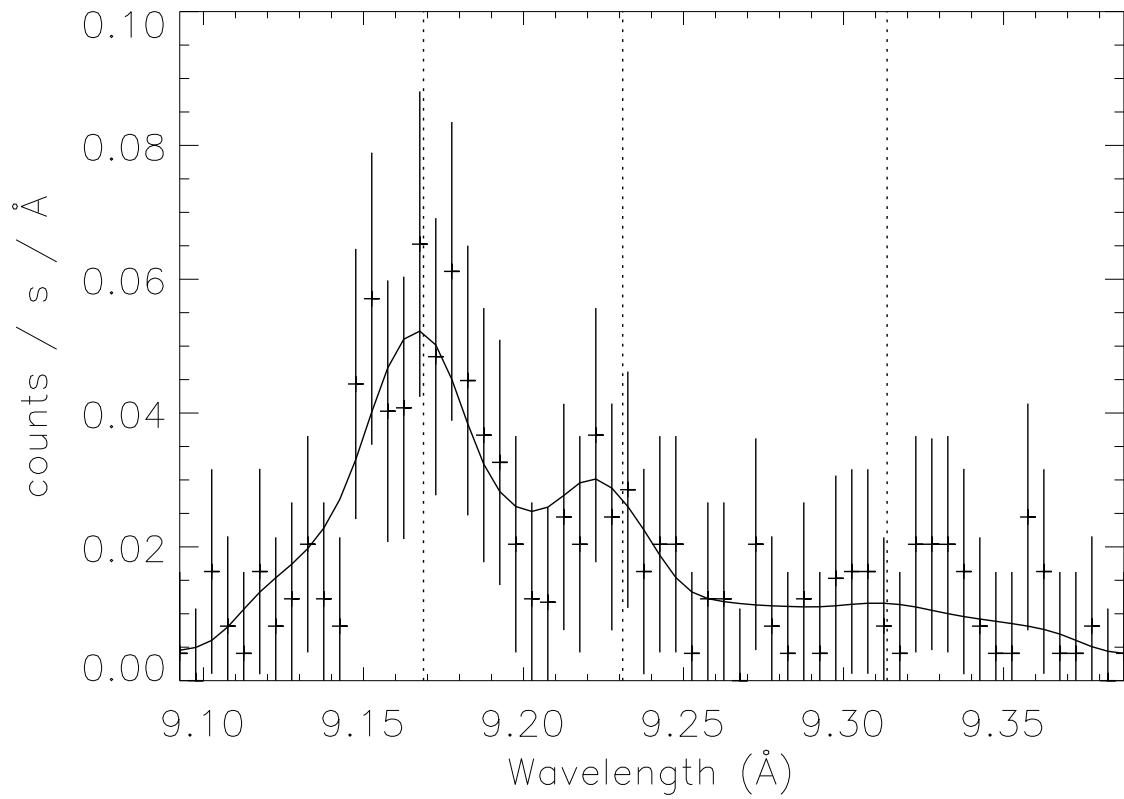


Fig. 21.— MEG data and best-fit model for Mg XI in  $\delta$  Ori. The positive and negative first order data have been coadded.

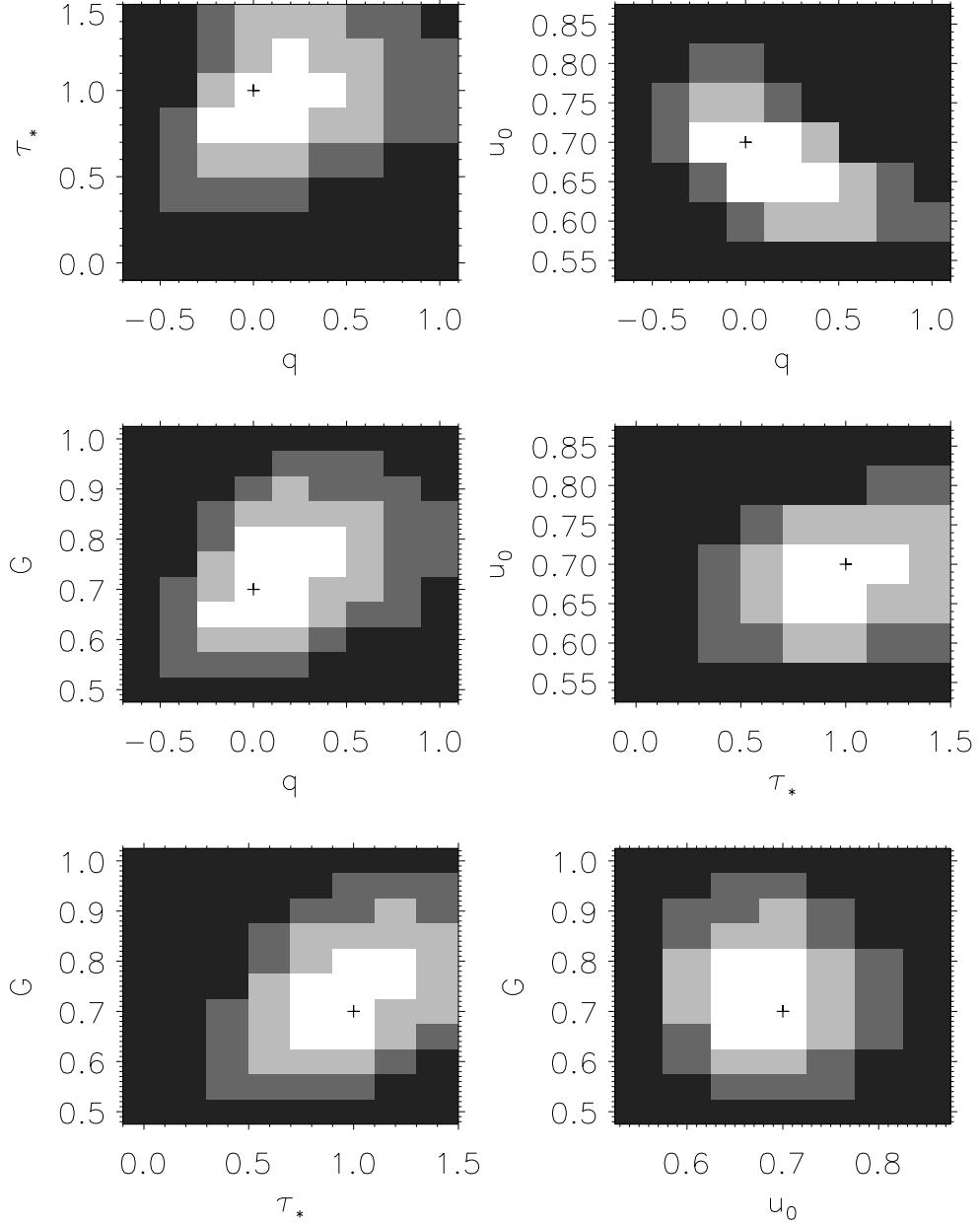


Fig. 22.— Two dimensional plots of confidence intervals for fit parameters for Mg XI in  $\zeta$  Pup. The shades of grey represent 1, 2, and 3  $\sigma$ , or  $\Delta C < 2.3, 6.17, 11.8$  (as appropriate for two degrees of freedom), and the cross represents the best fit. There is a moderate correlation of the fit parameters  $q$  and  $u_0$ , as one would expect. We have made similar plots for the other He-like profile fits (not shown) to look for correlations in fit parameters. These plots also show a moderate correlation between  $q$  and  $u_0$ .

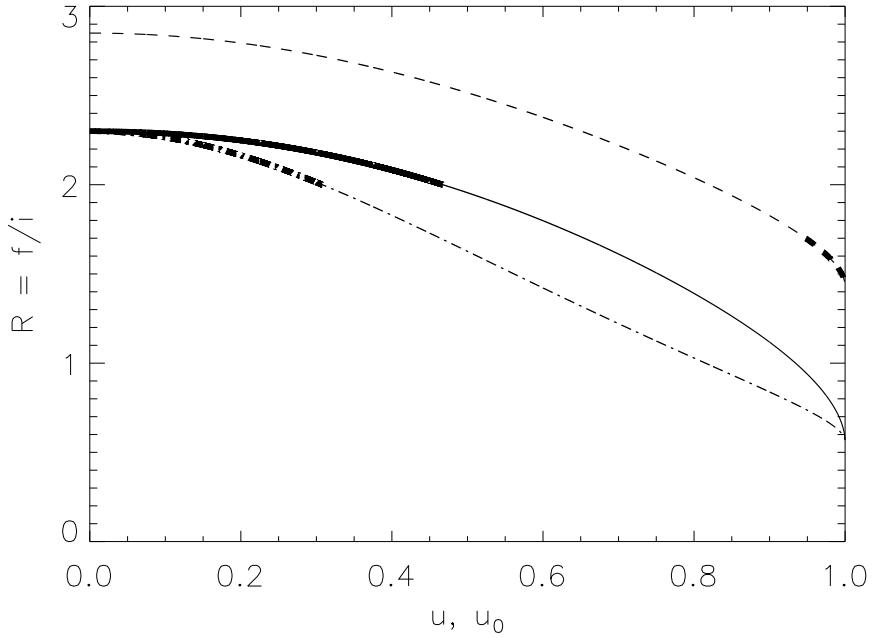


Fig. 23.— Comparison of measurements and calculations for Si XIII in  $\zeta$  Ori. Calculations are thin lines, and measurements are thickened over the allowed range of  $\mathcal{R}$ . The solid line shows  $\bar{\mathcal{R}}(u_0)$  from this work; the dash-dot line shows the  $\mathcal{R}(u)$  for a single radius, but using an averaged value of the TLUSTY UV flux; and the dashed line shows the calculations and measurements of Waldron & Cassinelli (2001). Note that the range shown by the thickened lines represents the allowed range of measured  $\mathcal{R}$  or  $\bar{\mathcal{R}}$  values, and does not represent the physical extent of the X-ray emitting plasma. In the case of  $\mathcal{R}$  the model assumes a single radius of formation, while for  $\bar{\mathcal{R}}$  the value of  $u_0$  inferred corresponds to the minimum radius for X-ray emission. The fact that the allowed range of  $\mathcal{R}$  graphically mimics the distribution of plasma radii for the upper limit value to  $u_0$  is a coincidence.

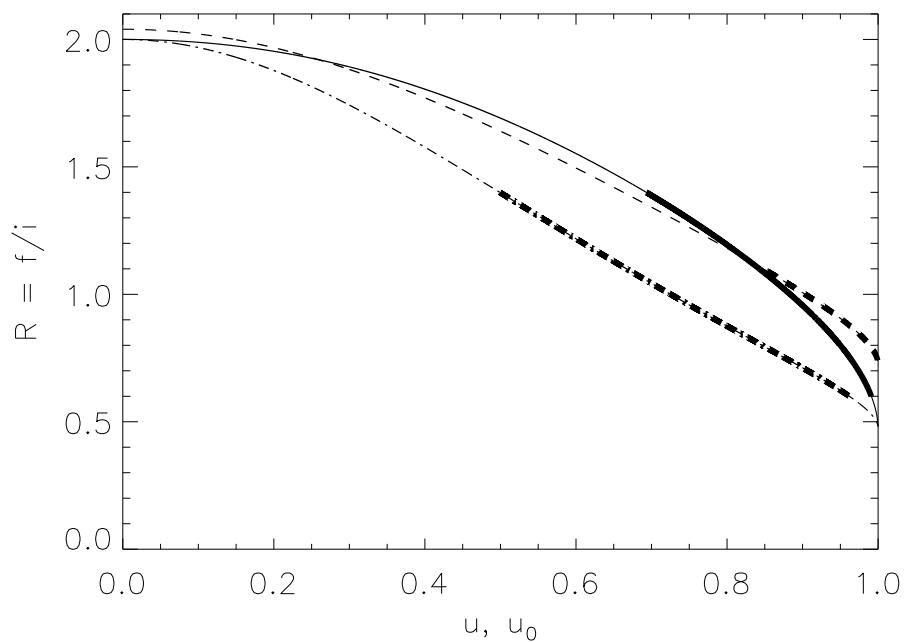


Fig. 24.— Same as Figure 23, but for S XV for  $\zeta$  Pup, and we are comparing our work to Cassinelli et al. (2001).